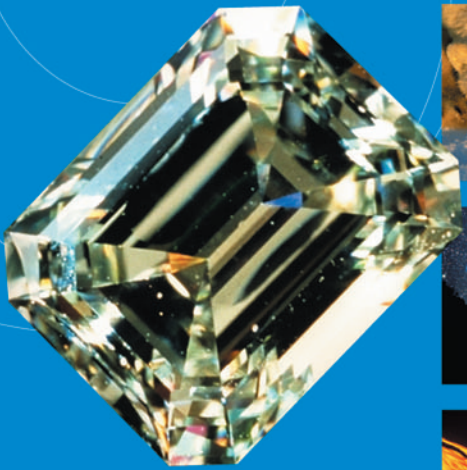
SCIENCE OF EVERYDAY THINGS

VOLUME 4: REAL-LIFE EARTH SCIENCE









EDITED BY NEIL SCHLAGER
WRITTEN BY JUDSON KNIGHT

SCIENCE OF EVERYDAY THINGS

VOLUME 3: REAL-LIFE BIOLOGY

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Science of Everyday Things
Volume 4: Real-Life Earth Science

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Contents

General Subject Index 413
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INTRODUCTION

Overview of the Series

Welcome to *Science of Everyday Things*. Our aim is to explain how scientific phenomena can be understood by observing common, real-world events. From luminescence to echolocation to buoyancy, the series will illustrate the chief principles that underlay these phenomena and explore their application in everyday life. To encourage cross-disciplinary study, the entries will draw on applications from a wide variety of fields and endeavors.

Science of Everyday Things initially comprises four volumes:

Volume 1: *Real-Life Chemistry*
Volume 2: *Real-Life Physics*
Volume 3: *Real-Life Biology*
Volume 4: *Real-Life Earth Science*

Future supplements to the series will expand coverage of these four areas and explore new areas, such as mathematics.

Arrangement of Real-Life Earth Science

This volume contains 40 entries, each covering a different scientific phenomenon or principle. The entries are grouped together under common categories, with the categories arranged, in general, from the most basic to the most complex. Readers searching for a specific topic should consult the table of contents or the general subject index.

Within each entry, readers will find the following rubrics:

- **Concept:** Defines the scientific principle or theory around which the entry is focused.
- **How It Works:** Explains the principle or theory in straightforward, step-by-step language.
- **Real-Life Applications:** Describes how the phenomenon can be seen in everyday life.
- **Where to Learn More:** Includes books, articles, and Internet sites that contain further information about the topic.

In addition, each entry includes a "Key Terms" section that defines important concepts discussed in the text. Finally, each volume includes many illustrations and photographs throughout.

Included in this volume, readers will find (in addition to the volume-specific general subject index), a cumulative general index, as well as a cumulative index of "everyday things." This latter index allows users to search the text of the series for specific everyday applications of the concepts.

About the Editor, Author, and Advisory Board

Neil Schlager and Judson Knight would like to thank the members of the advisory board for their assistance with this volume. The advisors were instrumental in defining the list of topics, and reviewed each entry in the volume for scientific accuracy and reading level. The advisors include university-level academics as well as high school teachers; their names and affiliations are listed elsewhere in the volume.

Neil Schlager is the president of Schlager Information Group Inc., an editorial services company. Among his publications are *When*

Technology Fails (Gale, 1994); *How Products Are Made* (Gale, 1994); the *St. James Press Gay and Lesbian Almanac* (St. James Press, 1998); *Best Literature By and About Blacks* (Gale, 2000); *Contemporary Novelists*, 7th ed. (St. James Press, 2000); *Science and Its Times* (7 vols., Gale, 2000-2001); and *Science in Dispute* (Gale, 2002). His publications have won numerous awards, including three RUSA awards from the American Library Association, two Reference Books Bulletin/Booklist Editors' Choice awards, two New York Public Library Outstanding Reference awards, and a *CHOICE* award for best academic book.

Judson Knight is a freelance writer, and author of numerous books on subjects ranging from science to history to music. His work on science includes *Science, Technology, and Society, 2000 B.C.-A.D.* 1799 (U•X•L, 2002), as well as extensive contributions to Gale's seven-volume *Science and Its Times* (2000-2001). As a writer on history, Knight has published *Middle Ages Reference Library* (2000), *Ancient Civilizations* (1999), and a volume in U•X•L's *African American Biography* series (1998). Knight's publications in the realm of music include *Parents Aren't Supposed to Like It* (2001), an overview of contemporary performers and genres, as well as *Abbey Road to Zapple Records: A Beatles Encyclopedia* (Taylor, 1999).

COMMENTS AND SUGGESTIONS

Your comments on this series and suggestions for future editions are welcome. Please write: The Editor, *Science of Everyday Things,* Gale Group, 27500 Drake Road, Farmington Hills, MI 48331-3535.

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UNDERSTANDING THE EARTH SCIENCES

EARTH, SCIENCE, AND NONSCIENCE

GEOSCIENCE AND EVERYDAY LIFE

EARTH SYSTEMS

EARTH, SCIENCE, AND NONSCIENCE

CONCEPT

To understand the composition and structure of Earth, one must comprehend the forces that shaped it. Much the same is true of the earth sciences themselves, which originated from attempts to explain the origins of Earth and the materials of which it is composed. Before the modern era, such explanations had roots in religion, mythology, or philosophy and drew from preconceived ideas rather than from observed data. A turning point came with the development of the scientific method, a habit of thinking that spread from astronomy and physics to chemistry and the earth sciences.

HOW IT WORKS

Aristotle's Four Causes

Though the Greek philosopher Aristotle (384–322 B.C.) exerted a negative influence on numerous aspects of what became known as the physical sciences (astronomy, physics, chemistry, and the earth sciences), he is still rightly regarded as one of the greatest thinkers of the Western world. Among his contributions to thought was the identification of four causes, or four approaches to the question of how and why something exists as it does.

In Aristotle's system, which developed from ideas of causation put forward by his predecessors, the most basic of explanations is the *material cause,* or the substance of which a thing is made. In a house, for instance, the wood and other building materials would be the material cause. The builders themselves are the *efficient cause,* or the forces that shaped the house. More complex than these is a third variety of cause-effect relationship, the *formal cause*—that is, the design or blueprint on which something is modeled.

The first three Aristotelian causes provide a pathway for explaining *how;* the fourth and last cause approaches the much more challenging question of *why.* This is the *final cause,* or the reason why a thing exists at all—in other words, the purpose for which it was made. Even in the case of the house, this is a somewhat complicated matter. A house exists, of course, to provide a dwelling for its occupants, but general contractors would not initiate the building process if they did not expect to make a profit, nor would the subcontractors and laborers continue to work on it if they did not earn an income from the project.

Religion, Science, and Earth

The matter of final cause is almost unimaginably more complex when applied to Earth rather than to a house. The question "Why does Earth exist?" or "What is the ultimate reason for Earth's existence?" is not really a topic for science at all, but rather for theology and philosophy. Nor do the answers provided by religion and philosophical beliefs qualify as answers in the same sense that workable scientific theories do.

There has always been a degree of tension between religion and the sciences, and nowhere has this been more apparent than in the earth sciences. As will be discussed later in this essay, most early theories concerning Earth's structure and development were religious in origin, and even some modern explanations have theological roots. Certainly there is nothing wrong with a



Engraving after a marble bust of Aristotle. *(Library of Congress.)*

scientist having religious beliefs, as long as those beliefs do not provide a filter for all data. If they do, the theologically minded scientist becomes rather like a mathematician attempting to solve a problem on the basis of love rather than reason. Most people would agree that love is higher and greater than mathematics; nonetheless, it has absolutely no bearing on the subject.

SCIENTIFIC ANSWERS AND THE SEARCH FOR A DESIGNER. The third, or formal, cause is less fraught with problems than the final cause when applied to the study of Earth, yet it also illustrates the challenges inherent in keeping science and theology separate. Does Earth have a "design," or blueprint? The answer is yes, no, and maybe. Yes, Earth has a design in the sense that there is an order and a balance between its components, a subject discussed elsewhere with reference to the different spheres (geosphere, hydrosphere, biosphere, and atmosphere). The physical evidence, however, tends to suggest a concept of design quite different from the theistic notion of a deity who acts as creator.

Consider, for example, the ability of an animal to alter its appearance as a means of blending in with its environment, to ward off predators, to disguise itself while preying upon other animals, or for some other purpose. On the one hand, this seems like an example of conscious design by a loving creator, but as Charles Darwin (1809–1882) showed, it may simply be a matter of adaptability. According to Darwin, members of species unable to alter their appearance died out, leading to the dominance of those who could camouflage themselves.

In fact, science is not really capable of addressing the matter of a Designer (i.e., God), and thus, for scientists, the question of a deity's role in nature is simply irrelevant. This is not because scientists are necessarily atheists (many are and have been dedicated men and women of faith) but because the concept of a deity simply adds an unnecessary step to scientific analysis.

This is in line with Ockham's razor, a principle introduced by the medieval English philosopher William of Ockham (*ca.* 1285?–1349). According to Ockham, "entities must not be unnecessarily multiplied." In other words, in analyzing any phenomenon, one should seek the simplest and most straightforward explanation. Scientists are concerned with hard data, such as the evidence obtained from rock strata. The application of theological ideas in such situations would at best confuse and complicate the process of scientific analysis.

THE ARGUMENT FROM DESIGN. A few years before Ockham, the Italian philosopher Thomas Aquinas (1224 or 1225–1274) introduced a philosophical position known as the "argument from design." According to Aquinas, whose idea has been embraced by many up to the present day, the order and symmetry in nature indicate the existence of God. Some philosophers have conceded that this order does indeed indicate the existence of *a* god, though not necessarily the God of Christianity. Science, however, cannot afford to go even that far: where spiritual matters are concerned, science must be neutral.

Does any of this disprove the existence of God? Absolutely not. Note that science must be *neutral,* not in opposition, where spiritual matters are concerned. Indeed, one could not disprove God's existence scientifically if one wanted to do so; to return to the analogy given earlier, such an endeavor would be akin to using mathematics to disprove the existence of love. Religious matters are simply beyond the scope of science,

and to use science against religion is as misinformed a position as its opposite.

Science and the first two causes. To return to Aristotle's causes, let us briefly consider the material and efficient cause as applied to the subject of Earth. These are much simpler matters than formal and final cause, and science is clearly able to address them. An understanding of Earth's material cause—that is, its physical substance—requires a brief examination of the chemical elements. The elements are primarily a subject for chemistry, though they are discussed at places throughout this book, inasmuch as they relate to the earth sciences and, particularly, geochemistry. Furthermore, the overall physical makeup of Earth, along with particular aspects of it, are subjects treated in much greater depth within numerous essays concerning specific topics, such as sedimentation or the biosphere.

Likewise the efficient cause, or the complex of forces that have shaped and continue to shape Earth, is treated in various places throughout this book. In particular, the specifics of Earth's origins and the study of these origins through the earth sciences are discussed in essays on aspects of historical geology, such as stratigraphy. Here the origins of Earth are considered primarily from the standpoint of the historical shift from mythological or religious explanations to scientific ones.

Real-Life Applications

Mythology and Geology

Most of what people believed about the origins and makeup of Earth before about 1700 bore the imprint of mythology or merely bad science. Predominant among these theories were the Creation account from the biblical Book of Genesis and the notion of the four elements inherited from the Greeks. These four elements—earth, air, fire, and water—were said to form the basis for the entire universe, and thus every object was thought to be composed of one or more of these elements. Thanks in large part to Aristotle, this belief permeated (and stunted) the physical sciences.

To call the biblical Creation story mythology is not, in this context at least, a value judgment. The Genesis account is not scientific, however, in the sense that it was not written on the basis of observed data but rather from religious principles. The concept of the four elements at least relates somewhat to observation, but specifically to untested observation; for this reason, it is hardly more scientific than the Genesis Creation story. The four elements were not, strictly speaking, a product of mythology, but they were mythological in the pejorative sense—that is, they had no real basis in fact.

Geomythology. The biblical explanation of Earth's origins is but one of many creation myths, part of a larger oral and literary tradition that Dorothy B. Vitaliano, in her 1973 book *Legends of the Earth,* dubbed *geomythology.* Examples of geomythology are everywhere, and virtually every striking natural feature on Earth has its own geomythological backdrop. For instance, the rocky outcroppings that guard the western mouth of the Mediterranean, at Gibraltar in southern Spain and Ceuta in northern Morocco, are known collectively as the Pillars of Hercules because the legendary Greek hero is said to have built them.

Geomythological stories can be found in virtually all cultures. For instance, traditional Hawaiian culture explains the Halemaumau volcano, which erupted almost continuously from 1823 to 1924, as the result of anger on the part of the Tahitian goddess Pele. Native Americans in what is now Wyoming passed down legends concerning the grooves along the sides of Devils Tower, which they said had been made by bears trying to climb the sides to escape braves hunting them.

Greek geomythology. In Western culture, among the most familiar examples of geomythology, apart from those in the Bible, are the ones that originated in ancient Greece and Rome. The Pillars of Hercules represents but one example. In particular, the culture of the Greeks was infused with geomythological elements. They believed, for instance, that the gods lived on Mount Olympus and spoke through the Delphic Oracle, a priestess who maintained a trancelike state by inhaling intoxicating vapors that rose through a fault in the earth.

Much of Greek mythology is actually geomythology. Most of the principal Greek deities ruled over specific aspects of the natural world that are today the province of the sciences, and many of them controlled realms now studied by the earth sciences and related disciplines. Certain branches of geology today are concerned

with Earth's interior, which the Greeks believed was controlled by Hades, or the Roman god Pluto. Volcanoes and thunderbolts were the work of the blacksmith god Hephaestus (the Roman deity Vulcan), while Poseidon (known to the Romans as Neptune) oversaw the area studied today by oceanographers.

ATLANTIS. Among the most persistent geomyths with roots in Greek civilization is the story of Atlantis, a continent that allegedly sank into the sea. Over the years, the myth grew to greater and greater dimensions, and in a blurring between the Atlantis myth and the biblical story of Eden, Atlantis came to be seen as a lost utopia. Even today, some people believe in Atlantis, and for scholarly endorsement they cite a passage in the writings of Plato (427?–347 B.C.). The great Greek philosopher depicted Atlantis as somewhere beyond the Pillars of Hercules, and for this reason its putative location eventually shifted to the middle of the Atlantic—an ocean in fact named for the "lost continent."

Given the layers of mythology associated with Atlantis, it may come as a surprise that the story has a basis in fact and that accounts of it appear in the folklore of peoples from Egypt to Ireland. It is likely that the myth is based on a cataclysmic event, either a volcanic eruption or an earthquake, that took place on the island of Crete, as well as nearby Thíra, around 1500 B.C. This cataclysm, some eight centuries before the rise of classical Greek civilization, brought an end to the Minoan civilization centered around Knossos in Crete. Most likely it raised vast tidal waves, or tsunamis, that reached lands far away and may have caused other cities or settlements to disappear beneath the sea.

BIBLICAL GEOMYTHOLOGY. As important as such Greek stories are, no geomythological account has had anything like the impact on Western civilization exerted by the first nine chapters of the Bible. These chapters contain much more than geomythology, of course; in fact, they introduce the central themes of the Bible itself: righteousness, sin, redemption, and God's covenant with humankind. In these nine chapters (or, more properly, eight and a half chapters), which cover the period from Earth's creation until the Great Flood, events are depicted as an illustration of this covenant. Thus, in 9 Genesis, when God introduces the rainbow after the Flood, he does so with the statement that it is a sign of his promise never again to attempt to destroy humanity.

As with Atlantis, the story of the Great Flood appears in other sources as well. Its antecedents include the Sumerian Gilgamesh epic, which originated in about 2000 B.C., a millennium before the writing of the biblical account. Also as in the case of Atlantis, the biblical flood seems to have a basis in fact. Some modern scientists theorize that the Black Sea was once a freshwater lake, until floods covered the land barriers that separated it from saltwater.

The Flood occupies chapters 6 through 9 of Genesis, while chapters 3 through 5 are concerned primarily with human rather than geologic events. The story of Adam, Eve, the serpent, and the fruit of the Tree of Knowledge is a beautiful, complex, and richly symbolic explanation of how humans, born innocent, are prone to sin. It is the first conflict between God and human, just as Cain's murder of Abel is the first conflict between people. Both stories serve to illustrate the themes mentioned earlier: in both cases, God punishes the sins of the humans but also provides them with protection as a sign of his continued faithfulness.

THE BIBLE AND SCIENCE. In fact, the entire Creation story, source of centuries' worth of controversy, occupies only two chapters, and this illustrates just how little attention the writers of the Bible actually devoted to "scientific" subjects. Certainly, many passages in the Bible describe phenomena that conflict with accepted scientific knowledge, but most of these fall under the classification of miracles—or, if one does not believe them, alleged miracles. Was Jesus born of a virgin? Did he raise the dead? People's answers to those questions usually have much more to do with their religious beliefs than with their scientific knowledge.

Most of the biblical events related to the earth sciences appear early in the Old Testament, and most likewise fall under the heading of "miracles." Certain events, such as the parting of the Red Sea by Moses, even have possible scientific explanations: some historians believe that there was actually an area of dry land in the Red Sea region and that Moses led the children of Israel across it. The account of Joshua causing the Sun to stand still while his men marched around the city of Jericho is a bit more difficult to square with science, but a believer might say that the Sun (or rather, Earth) *seemed* to stand still.

In any case, the Bible does not present itself as a book of science, and certainly the Israelites of ancient times had little concept of science as we know it today. Some of the biblical passages mentioned here have elicited controversy, but few have inspired a great deal of discussion, precisely because they are generally regarded as accounts of miracles. The same is not true, however, of the first two chapters of Genesis, which even today remain a subject of dispute in some quarters.

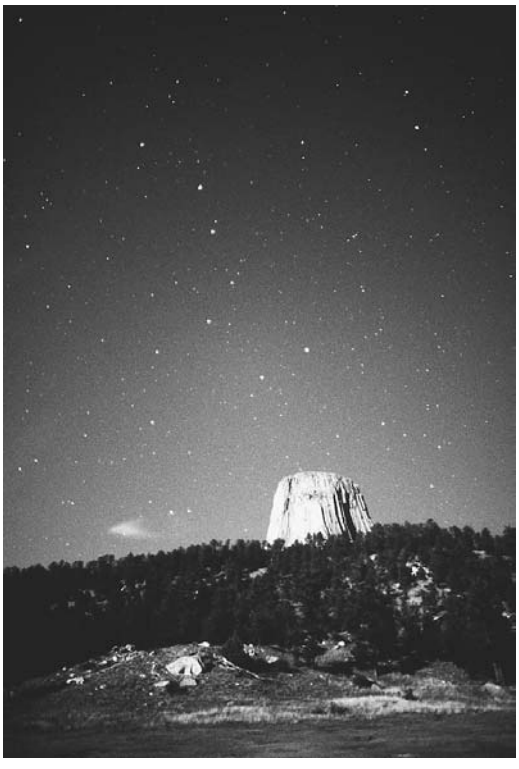
SIX DAYS? Actually, 2 Genesis concerns Adam's life before the Fall as well as the creation of Eve from his rib, so the Creation story proper is confined to the first chapter. One of the most famous passages in Western literature, 1 Genesis describes God's creation of the universe in all its particulars, each of which he spoke into being, first by saying, "Let there be light." After six days of activity that culminated with the creation of the human being, he rested, thus setting an example for the idea of a Sabbath rest day.

As prose poetry, the biblical Creation story is among the great writings of all time. It is also a beautiful metaphoric description of creation by a loving deity; but it is not a guide to scientific study. Yet for many centuries, Western adherence to the Genesis account (combined with a number of other factors, including the general stagnation of European intellectual life throughout much of the medieval period) forced a virtual standstill of geologic study. The idea that Earth was created in 144 hours reached its extreme with the Irish bishop James Ussher (1581–1656), who, using the biblical genealogies from Adam to Christ, calculated that God finished making Earth at 9:00 A.M. on Sunday, October 23, 4004 B.C.

The Myth of the Four Elements

Religion alone is far from the only force that has slowed the progress of science over the years. Sometimes the ideas of scientists or philosophers themselves, when formed on the basis of something other than scientific investigation, can prove at least as detrimental to learning. Such is the case when thinkers become more dedicated to the theory than to the pursuit of facts, as many did in their adherence to the erroneous concept of the four elements.

Today scientists understand an element as a substance made up of only one type of atom, meaning that unlike a compound, it cannot be broken down chemically into a simpler substance. This definition developed over the period from about 1650 to 1800, thanks to the British chemist Robert Boyle (1627–1691), who originated the idea of elements as the simplest substances; the French chemist Antoine Lavoisier (1743–1794), who first distinguished between elements and compounds; and the British chemist John Dalton (1766–1844), who introduced the atomic theory of matter.



Devils Tower, with the Big Dipper visible in the night sky. *(© Jerry Schad/Photo Researchers. Reproduced by permission.)*

During the twentieth century, with the discovery of the atomic nucleus and the protons within it, scientists further refined their definition of an element. Today elements are distinguished by atomic number, or the number of protons in the atomic nucleus. Carbon, for instance, has an atomic number 6, meaning that there are six protons in the carbon nucleus; therefore, any element with six protons in its atomic nucleus *must* be carbon.

ATOMIC THEORY VERSUS THE FOUR ELEMENTS. Atomic, or corpuscular, theory had been on the rise for some 150 years before Dalton, who built on ideas of predecessors that included Galileo Galilei (1564–1642)

and Sir Isaac Newton (1642–1727). In any case, the first thinker to conceive of atoms lived more than 2,000 years earlier. He was Democritus (*ca.* 460–*ca.* 370 B.C.), a Greek philosopher who described the world as being composed of indivisible particles—*atomos* in Greek. Democritus's idea was far from modern scientific atomic theory, but it came much closer than any other theory before the Scientific Revolution (*ca.* 1550–1700).

Why, then, did it take so long for Western science to come around to the atomic idea? The answer is that Aristotle, who exerted an almost incalculable impact on Muslim and Western thought during the Middle Ages, rejected Democritus' atomic theory in favor of the four elements theory. The latter had its roots in the very beginnings of Greek ideas concerning matter, but it was the philosopher Empedocles (*ca.* 490–430 B.C.) who brought the notion to some kind of maturity.

A NONSCIENTIFIC THEORY. According to the four elements theory, every object could be identified as a combination of elements: bone, for instance, was supposedly two parts earth, two parts water, and two parts fire. Of course, this is nonsense, and, in fact, none of the four elements are even really elements. Water comes the closest, being a compound of the elements hydrogen and oxygen. Earth and air are mixtures, while fire is the result of combustion, a form of oxidation-reduction chemical reaction.

Nonetheless, the theory had at least some basis in observation, since much of the physical world seems to include liquids, things that grow from the ground, and so on. Such observations alone, of course, are not enough to construct a theory, as would have become apparent if the Greeks had attempted to test their ideas. The ancients, however, tended to hold scientific experimentation in low esteem, and they were more interested in applying their intellects to the development of ideas than they were in getting their hands dirty by putting their concepts to the test.

THINKING IN FOURS. Aristotle explained the four elements as combinations of four qualities, or two pairs of opposites: hot/cold and wet/dry. Thus, fire was hot and dry, air was dry and cold, water was cold and wet, and earth was wet and hot. It is perhaps not accidental that there were four elements, four qualities, or even perhaps four Aristotelian causes.

Much earlier, the philosopher and mathematician Pythagoras (*ca.* 580–*ca.* 500 B.C.), who held that all of nature could be understood from the perspective of numbers, first suggested the idea of four basic elements because, he maintained, the number four represents perfection. This concept influenced Greek thinkers, including Empedocles and even Aristotle, and is also probably the reason for the expression *four corners of the world.*

That expression, which conveys a belief in a flat Earth, raises an important point that must be made in passing. Despite his many erroneous ideas, Aristotle was the first to prove that Earth is a sphere, which he showed by observing the circular shadow on the Moon during a lunar eclipse. This points up the fact that ancient thinkers may have been misguided in many regards, yet they still managed to make contributions of enormous value. In the same vein, Pythagoras, for all his strange and mystical ideas, greatly advanced scientific knowledge by introducing the concept that numbers can be applied to the study of nature.

In any case, the emphasis on fours trickled down through classical thought. Thus, the great doctors Hippocrates (*ca.* 460–*ca.* 377 B.C.) and Galen (129–*ca.* 199) maintained that the human body contains four "humors" (blood, black bile, green bile, and phlegm), which, when imbalanced, caused diseases. Humoral theory would exert an incalculable toll on human life throughout the Middle Ages, resulting in such barbaric medical practices as the use of leeches to remove "excess" blood from a patient's body. The idea of the four elements had a less clearly pernicious effect on human well-being, yet it held back progress in the sciences and greatly impeded thinkers' understanding of astronomy, physics, chemistry, and geology.

The Showdown Between Myth and Science

Aristotle's teacher Plato had accepted the idea of the four elements, but proposed that space is made up of a fifth, unknown element. This meant that Earth and the rest of the universe are fundamentally different, a misconception that prevailed for two millennia. Aristotle adopted that idea, as well as Plato's concept of a Demiurge, or Prime Mover, as Aristotle called it. Cen-

turies later Aquinas equated Aristotle's Prime Mover with the Christian God.

Building on these and other ideas, Aristotle proceeded to develop a model of the cosmos in which there were two principal regions: a celestial, or heavenly, realm above the orbit of the Moon and a terrestrial, or earthly, one in what was known as the sublunary (below the Moon) region. Virtually everything about these two realms differed. The celestial region never changed, whereas change was possible on Earth. Earth itself consisted of the four elements, whereas the heavens were made up of a fifth substance, which he called *ether.*

If left undisturbed, Aristotle theorized, the four elements would completely segregate into four concentric layers, with earth at the center, surrounded by water, then air, and then fire, bounded at the outer perimeter by the ether. The motion of bodies above the Moon's sphere caused the elements to behave unnaturally, however, and thus they remained mixed and in a constant state of agitation.

The distinction between so-called natural and unnatural (or violent) motion became one of the central ideas in Aristotle's physics, a scientific discipline whose name he coined in a work by the same title. According to Aristotle, all elements seek their natural position. Thus, the element earth tends to fall toward the center of the universe, which was identical with the center of Earth itself.

THE SCIENTIFIC REVOLUTION. On these and other ideas, Aristotle built a complex, systematic, and almost entirely incorrect set of principles that dominated astronomy and physics as well as what later became the earth sciences and chemistry. The influence of Aristotelian ideas on astronomy, particularly through the work of the Alexandrian astronomer Ptolemy (*ca.* 100–170), was especially pronounced.

It was through astronomy, the oldest of the physical sciences, that the Aristotelian and Ptolemaic model of the physical world ultimately was overthrown. This revolution began with the proof, put forward by Nicolaus Copernicus (1473–1543), that Earth is not the center of the universe. The Catholic Church, which had controlled much of public life in Europe for the past thousand years, had long since accepted Ptolemy's geocentric model on the reasoning that if the human being is created in God's image, Earth must be at the center of the universe. Copernicus' heliocentric (Sun-centered) cosmology therefore constituted a challenge to religious authority—a very serious matter at a time when the Church held the power of life and death.

Copernicus died before he suffered the consequences of his ideas, but Galileo, who lived much later, found himself in the middle of a debate between the Church and science. This conflict usually is portrayed in simplistic terms, with Galileo as the noble scientific genius defending reason against the powers of reaction, but the facts are much more complex. For centuries, the Church had preserved and encouraged learning, and the reactionary response to Copernican ideas must be understood in light of the challenges to Catholic authority posed by the Protestant Reformation. Furthermore, Galileo was far from diplomatic in his dealings, for instance, deliberately provoking Pope Urban VIII (1568–1644), who had long been a friend and supporter.

In any case, Galileo made a number of discoveries that corroborated Copernicus' findings while pointing up flaws in the ideas of Aristotle and Ptolemy. He also conducted studies on falling objects that, along with the laws of planetary motion formulated by Johannes Kepler (1571–1630), provided the basis for Newton's epochal work in gravitation and the laws of motion. Perhaps most of all, however, Galileo introduced the use of the scientific method.

THE SCIENTIFIC METHOD. The scientific method is a set of principles and procedures for systematic study using evidence that can be clearly observed and tested. It consists of several steps, beginning with observation. This creates results that lead to the formation of a hypothesis, an unproven statement about the way things are. Up to this point, we have gone no further than ancient science: Aristotle, after all, was making a hypothesis when he said, for instance, that heavy objects fall faster than light ones, as indeed they seem to do.

Galileo, however, went beyond the obvious, conducting experiments that paved the way for modern understanding of the acceleration due to gravity. As it turns out, heavy objects fall faster than light ones only in the presence of resistance from air or another medium, but in a vacuum a stone and a feather would fall at the same rate. How Galileo arrived at this idea is not important

KEY TERMS

ATOM: The smallest particle of an element, consisting of protons, neutrons, and electrons. An atom can exist either alone or in combination with other atoms in a molecule.

ATOMIC NUMBER: The number of protons in the nucleus of an atom.

COMPOUND: A substance made up of atoms of more than one element, chemically bonded to one another.

COSMOLOGY: A branch of astronomy concerned with the origin, structure, and evolution of the universe.

COSMOS: The universe.

ELEMENT: A substance made up of only one kind of atom. Unlike compounds, elements cannot be broken chemically into other substances.

GEOCENTRIC: Earth-centered.

GEOMYTHOLOGY: Folklore inspired by geologic phenomena.

HELIOCENTRIC: Sun-centered.

HYPOTHESIS: An unproven statement regarding an observed phenomenon.

LAW: A scientific principle that is shown always to be the case and for which no exceptions are deemed possible.

PHYSICAL SCIENCES: Astronomy, physics, chemistry, and the earth sciences.

PROTON: A positively charged particle in an atom.

SCIENTIFIC METHOD: A set of principles and procedures for systematic study that includes observation; the formation of hypotheses, theories, and ultimately laws on the basis of such observation; and continual testing and reexamination.

SCIENTIFIC REVOLUTION: A period of accelerated scientific discovery that completely reshaped the world. Usually dated from about 1550 to 1700, the Scientific Revolution saw the origination of the scientific method and the introduction of such ideas as the heliocentric (Sun-centered) universe and gravity.

THEORY: A general statement derived from a hypothesis that has withstood sufficient testing.

VACUUM: An area devoid of matter, even air.

here; rather, his application of the scientific method, which requires testing of hypotheses, is the key point.

If a hypothesis passes enough tests, it becomes a theory, or a general statement. An example of a theory is uniformitarianism, an early scientific explanation of Earth's origins discussed elsewhere, in the context of historical geology. Many scientific ideas remain theories and are quite workable as such: in fact, much of modern physics is based on the quantum model of subatomic behavior, which remains a theory. But if something always has been observed to be the case and if, based on what scientists know, no exceptions appear possible, it becomes a law. An example is Newton's third law of motion: no one has ever observed or created a situation in which a physical action does not yield an equal and opposite reaction.

Even laws can be overturned, however, and every scientific principle therefore is subjected to continual testing and reexamination, making the application of the scientific method a cyclical process. Thus, to be scientific, a principle must be capable of being tested. It should also be said that one of the hallmarks of a truly scientific theory is the attitude of its adherents. True scientists are

always attempting to *disprove* their own ideas by subjecting them to rigorous tests; the more such tests a theory survives, the stronger it becomes.

Creationism: Religion Under a Veil of Science

During the twentieth century, a movement called creationism emerged at the fringes of science. Primarily American in origin, creationism is a fundamentalist Christian doctrine, meaning that it is rooted in a strict literal interpretation of the Genesis account of Creation. (For this reason, creationism has little influence among Christians and Christian denominations not prone to literalism.) From the 1960s onward, it has been called *creation science,* but even though creationism sometimes makes use of scientific facts, it is profoundly unscientific.

Again, the reference to creationism as unscientific does not necessarily carry a pejorative connotation. Many valuable things are unscientific; however, to call creationism unscientific is pejorative in the sense that its adherents *claim* that it is scientific. The key difference lies in the attitude of creationists toward their theory that God created the Earth if not in six literal days, then at least in a very short time.

If this were a genuine scientific theory, its adherents would be testing it constantly against evidence, and if the evidence contradicted the theory, they would reject the theory, not the evidence. Science begins with facts that lead to the development of theories, but the facts always remain paramount. The opposite is true of creationism and other nonscientific beliefs whose proponents simply look for facts to confirm what they have decided is truth. Conflicting evidence simply is dismissed or incorporated into the theory; thus, for instance, fossils are said to be the remains of animals who did not make it onto Noah's ark.

Creationism (for which *The Oxford Companion to the Earth* provides a cogent and balanced explanation) is far from the only unscientific theory that has pervaded the hard sciences, the social sciences, or society in general. Others, aside from the four elements, have included spontaneous generation and the phlogiston theory of fire as well as various bizarre modern notions, such as flat-Earth theory, Holocaust or Moon-landing denial, and Afrocentric views of civilization as a vast racial conspiracy. Compared with Holocaust denial, for instance, creationism is benign in the sense that its proponents seem to act in good faith, believing that any challenge to biblical literalism is a challenge to Christianity itself.

Still, there is no justification for the belief that Earth is very young; quite literally, mountains of evidence contradict this claim. Nor is the idea of an old Earth a recent development; rather, it has circulated for several hundred years—certainly long before Darwin's theory of evolution, the scientific idea with which creationists take the most exception. For more about early scientific ideas concerning Earth's age, see Historical Geology and essays on related subjects, including Paleontology and Geologic Time. These essays, of course, are concerned primarily with modern theories regarding Earth's history, as well as the observations and techniques that have formed the basis for such theories. They also examine pivotal early ideas, such as the Scottish geologist James Hutton's (1726–1797) principle of uniformitarianism.

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GEOSCIENCE AND EVERYDAY LIFE

CONCEPT

How can learning about rocks help us in our daily lives? The short answer is that geology and the related geologic sciences (sometimes referred to collectively as *geoscience*) give us a glimpse of the great complexity inherent in the natural world, helping us appreciate the beauty and order of things. This, in turn, makes us aware of our place in the scheme of things, so that we begin to see our own daily lives in their proper context. Beyond that, the study of geoscientific data can give us an enormous amount of information of practical value while revealing much about the world in which we dwell. The earth sciences are, quite literally, all around us, and by learning about the structures and processes of our planet, we may be surprised to discover just how prominent a place geoscience occupies in our daily lives and even our thought patterns.

HOW IT WORKS

Why Study Geoscience?

One of the questions students almost always ask themselves or their teachers is "How will I use this?" or "What does all this have to do with everyday life?" It is easy enough to understand the application of classes involved in learning a trade or practical skill—for example, wood shop or a personal finance course. But the question of applicability sometimes becomes more challenging when it comes to many mathematical and scientific disciplines. Such is the case, for instance, with the earth sciences and particularly geoscience. Yet if we think about these concerns for just a moment, it should become readily apparent just why they are applicable to our daily lives.

After all, geoscience *is* the study of Earth, and therefore it relates to something of obvious and immediate practical value. We may think of a hundred things more important and pressing than studying Earth—romantic involvements, perhaps, or sports, or entertainment, or work (both inside and outside school)—yet without Earth, we would not even have those concerns. Without the solid ground beneath our feet, which provides a stage or platform on which these and other activities take place, life as we know it would be simply impossible. Our lives are bounded by the solid materials of Earth—rocks, minerals, and soil—while our language reflects the primacy of Earth in our consciousness. As we discuss later, everyday language is filled with geologic metaphors.

Defining Geoscience

The geologic sciences—geology, geophysics, geochemistry, and related disciplines—are sometimes referred to together as geoscience. They are united in their focus on the solid earth and the mostly nonorganic components that compose it. In this realm of earth science, geology is the leading discipline, and it has given birth to many offshoots, including geophysics and geochemistry, which represent the union of geology with physics and chemistry, respectively.

Geology is the study of the solid earth, especially its rocks, minerals, fossils, and land formations. It is divided into historical geology, which is concerned with the processes whereby Earth was formed, and physical geology, or the study of the materials that make up the planet. Geophysics addresses Earth's physical processes as well as its gravitational, magnetic, and electric

properties and the means by which energy is transmitted through its interior. Geochemistry is concerned with the chemical properties and processes of Earth—in particular, the abundance and interaction of chemical elements.

These subjects are of principal importance in this book. Though geology takes the lion's share of attention, geophysics and geochemistry each encompass areas of study essential to understanding our life on Earth: hence we look in separate essays at such geophysical subjects as Gravity and Geodesy or Geomagnetism as well as such geochemical topics as Biogeochemical Cycles, Carbon Cycle, and Nitrogen Cycle.

OTHER AREAS OF GEOSCIENCE. In addition to these principal areas of interest in geoscience, this book treats certain subdisciplines of geology as areas of interest in their own right. These include geomorphology and the studies of sediment and soil. Geomorphology is an area of physical geology concerned with the study of landforms, with the forces and processes that have shaped them, and with the description and classification of various physical features on Earth.

In contrast to geology, which normally is associated with rocks and minerals, geomorphology is concerned more with larger configurations, such as mountains, or with the erosive and weathering forces that shape such landforms. (See, for instance, essays on Mountains, Erosion, and Mass Wasting.) Erosion and weathering also play a major role in creating sediment and soil, areas that are of interest in the subdisciplines of sedimentology and soil science.

CONTRAST WITH OTHER DISCIPLINES AND SUBDISCIPLINES. Geoscience is distinguished sharply from the other branches of the earth sciences, namely, hydrologic sciences and atmospheric sciences. The first of these sciences, which is concerned with water, receives attention in essays on Hydrology and Hydrologic Cycle. The second, which includes meteorology (weather forecasting) and climatology, is the subject of the essays Weather and Climate.

In addition to the hydrologic and atmospheric sciences, there are areas of earth sciences study that touch on biology. Essays in this book that treat biosphere-related topics include Ecosystems and Ecology and Ecological Stress. There is one area or set of areas, however, in which geoscience and biology more or less overlap: sedimentology and soil science, since soil is a combination of rock fragments and organic material (see Soil).

THE TERRITORY OF GEOSCIENCE

The organic material in soil—dead plants and animals and parts thereof—has ceased to be part of the biosphere and is part of the geosphere. The geosphere encompasses the upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources. (For more about the "spheres," see Earth Systems.)

Later in this essay, we discuss several areas of geoscientific study that take place close to the surface of Earth. Yet the territory of geoscience extends far deeper, going well below the geosphere into the interior of the planet. (For more on this subject, see Earth's Interior.) Geoscience even involves the study of "earths" other than our own; as discussed in such essays as Planetary Science and Sun, Moon, and Earth, there is considerable overlap between geoscience and astronomy.

REAL-LIFE APPLICATIONS

THE PRIMACY OF EARTH

We may not think about geoscience or earth science much, or at least we may not *think* that we think about these topics very much—and yet we spend our lives in direct contact with these areas. Certainly in a given day, every person experiences physics (the act of getting out of bed is an example of the third law of motion, discussed in Gravity and Geodesy) and chemistry (eating and digesting food, for instance), but the experience of geoscience is more direct: we can actually *touch* the earth.

Before the late nineteenth century and the introduction of processed foods, everything a person ate clearly either was grown in the soil or was part of an animal that had fed on plants grown in the soil. Even today, the most grotesquely processed products, such as the synthetic cream puffs sold at a convenience store, still hold a connection to the earth, inasmuch as they contain sugar—a natural product. In any

case, most of what we eat (especially in a health-conscious diet) has a close connection to the earth.

Geoscience and language. No wonder, then, that a number of creation stories, including the one in Genesis, depict humankind as coming from the soil—an account of origins reflected in the well-known graveside benediction "Ashes to ashes, dust to dust." Our language is filled with geoscientific metaphors, including such proverbs as "A rolling stone gathers no moss" or "Still waters run deep." (The latter aphorism, despite its hydrologic imagery, actually refers to the fact that in deeper waters, rock formations are, by definition, not likely to be near the surface. By contrast, in order for a "babbling brook" to make as much noise as it does, it must be flowing over prominent rocks.)

Then there are the countless geologic figures of speech: "rock solid," "making mountains out of molehills," "cold as a stone," and so on. When the rock musician Bob Seger sang, in a 1987 hit, about being "Like a Rock" as a younger man, listeners knew exactly what he meant: solid, strong, dependable. So established was the metaphor that a few years later, Chevrolet used the song in advertising their trucks and sport-utility vehicles (including, ironically, a vehicle whose name uses a somewhat less reassuring geologic image: the Chevy Avalanche).

The geomorphology of religious faith. Rocks and other geologic features have long captured the imagination of humans; hence, we have the many uses of mountains in, for instance, religious imagery. There was the mystic mountain paradise of Valhalla in Norse mythology as well as Mount Olympus in Greek myths and legends. Unlike Valhalla, Olympus is a real place; so, too, is Kailas in southwestern Tibet, which ancient adherents of the Jain religion called Mount Meru, the center of the cosmos, and which Sanskrit literature identifies as the paradise of Siva, one of the principal Hindu deities.

There is also Sri Pada, or Adam's Peak, in Sri Lanka, a spot sacred to four religions. Buddhists believe the mountain is the footprint of the Buddha, while Hindus call it the footprint of Siva. Muslims and Christians believe it to be the footprint of Adam. Then there are the countless mountain locales of the Old Testament, including Ararat (in modern Turkey), where Noah's ark ran aground, and Sinai (in the Sinai Desert between Egypt and Israel), where Moses was called by God and later received the Ten Commandments.

The New Testament account of the life of Jesus Christ is punctuated throughout with geologic and geomorphologic details: the temptations in the desert, the Sermon on the Mount, and the Transfiguration, which probably took place atop Mount Tabor in Israel. He was crucified on a hill, buried in a cave, rolled a stone away at his Resurrection, and finally ascended to heaven from the Mount of Olives.

Arts, Media, and the Geosciences

From ancient times rocks and minerals have intrigued humans, not only by virtue of their usefulness but also because of their beauty. On one level there is the purely functional use of rock as a building material, and on another level there is the aesthetic appreciation for the beauty imparted by certain types of rock, such as marble.

Rock is an excellent building material when it comes to compression, as exerted by a great weight atop the rock; in the case of tension or stretching, however, rock is very weak. This shortcoming of stone, which was otherwise an ideal building material for the ancients (given its cheapness and relative abundance in some areas of the world), led to one of history's great innovations in architecture and engineering: the arch. A design feature as important for its aesthetic value as for its strength, the arch owed its physical power to the principle of weight redistribution. Arched Roman structures two thousand or more years old still stand in Europe, a tribute to the interaction of art, functionality, and geoscience.

The visual arts. *The Oxford Companion to the Earth* contains a number of excellent entries on the relationship between geoscience and the arts. In the essay "Art and the Earth Sciences," for instance, Andrew C. Scott notes four ways in which the earth sciences and the visual arts (including painting, sculpture, and photography) interact: through the depiction of such earth sciences phenomena as mountains or storms, through the use of actual geologic illustrations or even maps as forms of artwork, through the application of geologic materials in art (most notably, marble in sculpture), and



While stone is a strong building material in terms of compression, it is weak in terms of tension. The arch owes its strength to the principle of weight distribution, which overcomes this shortcoming of stone. Indeed, the Roman Coliseum has stood for more than two thousand years. *(© John Moss/Photo Researchers. Reproduced by permission.)*

through the employment of geology to investigate aspects of art objects (for instance, determining the origins of materials in ancient sculpture).

In the first category, visual depictions of geologic phenomena, Scott mentions works by unknown artists of various premodern civilizations (in particular, China and Japan) as well as by more recent artists whose names are hardly household words. On the other hand, some extremely well known figures produced notable works related to geoscience and the earth sciences. For example, the Italian artist and scientist Leonardo da Vinci (1452–1519), who happened to be one of the fathers of geology (see Studying Earth), painted many canvases in which he portrayed landscapes with a scientist's eye.

Another noteworthy example of earth sciences artwork and illustration is *The Great Piece of Turf* (1503), by Leonardo's distinguished contemporary the German painter and engraver Albrecht Dürer (1471–1528). A life-size depiction of grasses and dandelions, *Turf* belongs within the realm of earth sciences or even biological sciences rather than geoscience, yet it is significant as a historical milestone for all natural sciences.

In creating this work, Dürer consciously departed from the tradition, still strong even in



Scientific illustration became popular between 1500 and 1700, bridging the boundary between earth science and art. This map of the world, surrounded by allegorical scenes depicting the rewards and pitfalls of exploration, dates to 1689. *(© G. Bernard/Photo Researchers. Reproduced by permission.)*

the Renaissance, of representing "important" subjects, such as those of the Bible and classical mythology or history. By contrast, Dürer chose a simple scene such as one might find at the edge of any pond, yet his painting had a tremendous artistic and scientific impact. He set a new tone of naturalism in the arts and established a standard for representing nature as it is rather than in the idealized version of the artist's imagination.

As a result of Dürer's efforts, the period between about 1500 and 1700 saw the appearance of botanical illustrations whose quality far exceeded that of all previous offerings. Thus, he started a movement that spread throughout the world of scientific illustrations in general. Later, such geologists as England's William Smith (1769–1839) would produce maps that are rightly regarded as works of art in their own right (see Measuring and Mapping Earth).

Sometimes geologic phenomena have themselves become the basis for works of art, as Scott points out, observing that the modern American artist James Turrell once "set out to modify an extinct volcano, the Roden Crater [in northern Arizona], by excavating chambers and a tunnel to provide a visual experience of varying spatial relationships, the effects of light, and the perception of the sky." Elsewhere in the *Oxford Companion,* other writers show how evidence of a

geoscientific influence has appeared in other arts and media, including music.

MUSIC. In "Music and the Earth Sciences," D. L. Dineley and B. Wilcock offer a fascinating overview of natural formations or materials that have their own musical qualities: for example, the "singing sands" of the Arabian peninsula and other regions, which produce musical tones when millions of grains are rubbed together by winds. The authors also discuss the effect of geologic phenomena on the sound and production of music—for instance, the acoustic qualities of music played in an auditorium built of stone.

Then there is the subject of musical compositions inspired by geoscientific or earth sciences phenomena. Among them are *The Hebrides; or, Fingal's Cave* by the German composer Felix Mendelssohn (1809–1847) as well as one the authors do not mention: *The Planets,* presented in 1918 by the German composer Gustav Holst (1874–1934). One also might list popular songs that refer to such phenomena, including "The White Cliffs of Dover." Written by Walter Kent and Nat Burton in 1941, the song epitomizes the longing for peace in a world torn by war. The cliffs themselves, which guard the eastern approaches of Britain, sometimes are referred to incorrectly as "chalk," though they are made of gypsum.

Ironically, rock music has few significant songs that refer to rocks. Usually the language is metaphoric, as was the case with the Bob Seger song discussed earlier. Hence, we have the name of the rock group Rolling Stones (with its implicit reference to the proverbial saying mentioned earlier) as well as the title to one of their earliest hits, "Heart of Stone." Jim Morrison's lyrics for the Doors include several references to the ground and things underneath it, including a gold mine in "The End." Coal mines have appeared in more than one song: "Working in the Coal Mine" was a hit for Lee Dorsey in the 1960s and was performed anew by the group Devo in 1981—not long after the Police song "Canary in a Coal Mine" appeared.

FILM. More significantly, the year 1981 marked the release of *Raiders of the Lost Ark,* a film cited as a major turning point by Ted Nield in the *Oxford Companion*'s "Geoscience in the Media" entry. The film is not about a geoscientist but an archaeologist, Indiana Jones (played by the actor Harrison Ford); however, the character of Jones is based on an American paleontologist, Roy Chapman Andrews (1884–1960). Earlier movies, Nield observes, had portrayed the typical scientist as an "egghead . . . an arrogant, unworldly, megalomaniac obsessive . . . But with Indiana Jones we saw the beginning of a reaction. Increasing audience sophistication is part of the reason."

Nield goes on to discuss the movie *Jurassic Park* (1993), which features three scientists, all of whom receive positive treatment. The actor Sam Neill, as a paleontologist, is described as "dedicated—perhaps a bit too educated—but also intuitive, a superb communicator, and above all, knowledgeable about dinosaurs." Laura Dern, playing a paleobiologist, is "strong-willed, independent, feminist, and sexy," while Jeff Goldblum's mathematician is "weird, roguish, and cool." Sparking a widespread interest in dinosaurs and paleontology, the film (a major box-office hit directed by Steven Spielberg) helped advance the cause of the geosciences.

The positive trend in movie portrayals of geoscientists, Nield states, continued in *Dante's Peak* (1997), in which even the casting of the ultra-handsome actor Pierce Brosnan as a geologist says a great deal about changing perceptions of scientists. Noting that audiences had come to differentiate between science and the misapplication thereof, Nield observes that "The heat seems to have come off those who are merely curious about Nature's workings." Additionally, "by being associated with the open air and fieldwork, [geoscientists] can take on some of the clichéd but healthy characteristics usually associated on film with oilmen and lumberjacks."

In an entirely different category is another fascinating example of geoscience in film, Australian director Peter Weir's *Picnic at Hanging Rock* (1975). Weir, who went on to make such well-known films as *The Year of Living Dangerously* (1982), *Witness* (1985), and *Dead Poets' Society* (1989), established his reputation—and that of Australian cinema in general—with *Picnic,* which concerns the disappearance of a group of schoolgirls and their teacher on Valentine's Day, 1900. The story itself is fictional, though it seems otherwise (*Picnic* later inspired *The Blair Witch Project,* which also presents fiction as fact); however, the rock in the title is very much a real place. In the film, Hanging Rock is by far the

most striking character, a brooding presence whose foreboding features serve as a reminder of Earth's vastness and great age in the face of human insignificance.

The Work of Geoscientists

The work of the geoscientist indeed is associated with the open air to a much greater degree than that of the physicist or chemist; on the other hand, a geoscientist might very well work indoors, for instance, as a teacher. Prospective geoscientists who subscribe to a worldview of environmental utopianism can get a job "saving the world"—perhaps even working for starvation wages, so as to heighten the nobility of the undertaking. On the other hand, a pragmatist can go to work for an "evil" oil company and make a good living. The point is that there is a little of something for everyone in the world of geoscience.

Geoscientists may work for educational institutions, governments, or private enterprise. They may be involved in the search for energy resources, such as coal or oil (or even uranium for nuclear power), or they may be put to work searching for valuable and precious metals ranging from iron to gold. They even may be employed in the mining of diamonds or other precious gems in South Africa, Russia, or other locales. Other, perhaps less glamorous but no less important resources for which geoscientists in various roles search are water as well as rocks, clay, and minerals for building.

The majority of employed geoscientists work for industry but not always in the capacity of resource extraction. Some are involved in environmental issues; indeed, environmental geology—the application of geologic techniques to analyze, monitor, and control the environmental impact of natural and human phenomena—is a growing field. Among the areas of concern for environmental geologists are water management, waste disposal, and land-use planning.

Environmental and urban geology. Many environmental geologists, as one might expect, are employed by governments. They may be involved in soil studies before the commencement of a building project, in analyzing the necessary thickness and materials for a particular stretch of road, or in designing and establishing specifications for a landfill. Many such concerns come into play when large populations gather together. In fact, a growing area of specialization in environmental geology is urban geology.

Urban geology can be defined as the application of geologic techniques to the study of the built environment. (The latter term is architectural and engineering jargon for any physical or geographic area containing human construction.) At first, "urban geology" might almost seem like an oxymoron, since the term geology usually calls to mind vast, unpopulated mountain ranges and rock formations—perhaps in South Dakota or Wyoming. In fact, geology is a major factor in the development of cities. Most are defined by their geomorphology: the hills of Athens and Rome, the mountains above Los Angeles, or the harbors of New York and other major ports, for instance.

Most cities have natural barriers to growth, and this is precisely because geomorphology originally dictated the location at which the city was established. A rare exception is Atlanta, Georgia, which grew around the point where several rail lines met. (In the 1840s, when it was established, it bore the name Terminus, a reference to the fact that it lay at the end of the rail line.) Bounded by no ocean, significant rivers, mountains, or other natural barriers, such as deserts, Atlanta began a period of explosive growth in the latter part of the twentieth century and has never stopped growing. Today Atlanta is a textbook example of urban sprawl: lacking a vital city center, it is a settlement of some four million people spread over an area much larger than Rhode Island, with no end to growth in sight.

Los Angeles often is cited as a case of urban sprawl, but its problems are quite different: it is rife with geomorphologic barriers, including oceans, mountains, and desert. The result is increasing growth within a limited area, resulting in heightened stress on existing resources. These are some of the issues confronted by urban geologists. Another example is the problem of determining the strength of bedrock, which dictates the viability of tall buildings. Urban geologists also are concerned with such issues as underground facilities for transportation, infrastructure, and even usable workspace—one possible solution to the problem of urban sprawl.

Geoarchaeology and related fields. At the opposite extreme, in many ways, from urban geology is geoarchae-



A gold mine in Zimbabwe. Geoscientists work for educational institutions, governments, and private enterprise in such fields as resource extraction, environmental studies and management, and even archaeology and criminology. *(© Peter Bowater/Photo Researchers. Reproduced by permission.)*

ology, or the application of geologic analysis to archaeology and related fields. Whereas urban geology is concerned with the here and now, geoarchaeology—like the larger field of historical geology—addresses the past. And whereas urban geologists are most likely to be employed by governments, geoarchaeologists and those in similar areas are typically on the payroll of universities.

In a different sense, geoarchaeology also contrasts with archaeological geology, which is the study of archaeological sites for data relevant to the geosciences; thus, archaeological geology stands the approach of geoarchaeology on its head. An example of a study in archaeological geology can be found in the work conducted around the Roman ruins at Hierapolis in what is now Turkey. There, investigation of walls and gutters reveals the fact that the city was sitting astride an earthquake fault zone—a fact unknown to its residents, except when they experienced seismic tremors.

By contrast, an example of geoarchaeology in action would be establishing an explanation for how people came to the Americas from Siberia near the end of the last ice age—by crossing a land bridge that existed at that time. Another example of geoarchaeology would be the realm of ecclesiastical geology, which involves the study of old church masonry walls with the purpose of identifying areas from which rocks, bricks, and other materials were derived. Studies of medieval churches in England, for instance, show varieties of rock from sometimes unexpected locations, often placed alongside bricks taken from older Roman structures.

From the explanation and examples given here, it may be a bit hard to discern the difference between geoarchaeology and archaeological geology. Certainly there is a great deal of overlap, and in practice the difference comes down to a question of who is leading the fieldwork—a geologist or an archaeologist. In any case, both realms are concerned with the relatively recent human past, as opposed to the vast stretches of time that are the domain of historical geology (see Geologic Time).

FORENSIC GEOLOGY. On October 7, 2001, the United States launched air strikes against Afghanistan in retaliation for the refusal of that country's Taliban regime to surrender Osama bin Laden, the suspected mastermind of the World Trade Center bombing on September 11. On the same day, bin Laden's al-Qaeda ter-

KEY TERMS

ATMOSPHERIC SCIENCES: A major division of the earth sciences, distinguished from geoscience and the hydrologic sciences by its concentration on atmospheric phenomena. Among the atmospheric sciences are meteorology and climatology.

BIOSPHERE: A combination of all living things on Earth—plants, mammals, birds, reptiles, amphibians, aquatic life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

EARTH SCIENCES: The entire range of scientific disciplines focused on the study of Earth, including not only geoscience but also the atmospheric and hydrologic sciences.

ENVIRONMENTAL GEOLOGY: A field of geology involved in the application of geologic techniques to analyze, monitor, and control environmental impact of both natural and human phenomena.

GEOCHEMISTRY: A branch of the earth sciences, combining aspects of geology and chemistry, that is concerned with the chemical properties and processes of Earth—in particular, the abundance and interaction of chemical elements and their isotopes.

GEOLOGY: The study of the solid earth, in particular, its rocks, minerals, fossils, and land formations.

GEOMORPHOLOGY: An area of physical geology concerned with the study of landforms, with the forces and processes that have shaped them, and with the description and classification of various physical features on Earth.

GEOPHYSICS: A branch of the earth sciences that combines aspects of geology and physics. Geophysics addresses the planet's physical processes as well as its gravitational, magnetic, and electric properties and the means by which energy is transmitted through its interior.

rorist organization released a videotape of their leader delivering a diatribe against the United States. Naturally, military and law-enforcement agencies involved in the hunt for bin Laden took an interest in the tape, and some specialists sought clues in an unexpected place: the rocks behind bin Laden, featured prominently in the tape.

Although the efforts to trace bin Laden's location by the rock formations in the area were not successful, the underlying premise—that geographic regions have their own specific types and patterns of rock—was both a fascinating and a plausible one. This was just another example of a specialty known as forensic geology, or the use of geologic and other geoscientific data in solving crimes. Forensic geology has it origins around the beginning of the twentieth century, but some historians cite Sherlock Holmes, the master sleuth created by the English physician and writer Sir Arthur Conan Doyle (1859–1930), as an early practitioner.

In *The Sign of Four,* for instance, Holmes uses geologic data to ascertain that Watson has been to the Wigmore Street Post Office: "Observation tells me that you have a little reddish mould adhering to your instep," he explains. "Just opposite the Wigmore Street Office they have taken up the pavement and thrown up some earth, which lies in such a way that it is difficult to avoid treading in it in entering. The earth is of this peculiar reddish tint which is found, as far as I know, nowhere else in the neighbourhood."

The true founder of forensic geology was probably the Austrian jurist and pioneer in

KEY TERMS CONTINUED

GEOSCIENCE: The geologic sciences (geology, geochemistry, geophysics, and related disciplines), as opposed to other earth sciences—that is, atmospheric sciences, such as meteorology, and hydrologic sciences, such as oceanography.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

HISTORICAL GEOLOGY: The study of Earth's physical history. Historical geology is one of two principal branches of geology, the other being physical geology.

HYDROLOGIC SCIENCES: Areas of the earth sciences concerned with the study of the hydrosphere. Among these areas are hydrology, glaciology, and oceanography.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals) and oxides, such as carbon dioxide.

PHYSICAL GEOLOGY: The study of the material components of Earth and of the forces that have shaped the planet. Physical geology is one of two principal branches of geology, the other being historical geology.

PHYSICAL SCIENCES: Astronomy, physics, chemistry, and the earth sciences.

SEDIMENT: Material deposited at or near Earth's surface from a number of sources, most notably preexisting rock. Soil is derived from sediment, particularly the mixture of rock fragments and organic material.

criminology Hans Gross (1847–1915), whose *Handbuch für Untersuchungsrichter* (Handbook for examining magistrates, 1898) was a pivotal work in the field. "Dirt on shoes," wrote Gross, "can often tell us more about where the wearer of those shoes has last been than toilsome inquiries." Near the turn of the nineteenth century, Germany's Georg Popp, who operated a forensic laboratory in Frankfurt, used the new science effectively in two cases.

The first of these cases involved the murder of a woman named Eva Disch in October 1904. Among the items found at the murder scene was a dirty handkerchief containing traces of coal, snuff, and hornblende, a mineral. Popp matched the handkerchief with a suspect who worked at two locations that used a great deal of hornblende. In addition, the suspect's pants cuffs bore soil both from the murder scene and the victim's house.

Four years later, in investigating the murder of Margaethe Filbert in Bavaria, Popp ascertained that the soil at the crime scene was characterized by red quartz and red clay rich in iron. By contrast, the chief suspect had a farm whose fields were notable for their porphyry, milky quartz, and mica content. As it turned out, the suspect's shoes bore traces of quartz and red clay rather than those other minerals, even though he claimed he had been working in his fields when the crime occurred.

WHERE TO LEARN MORE

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EARTH SYSTEMS

CONCEPT

A system is any set of interactions set apart from the rest of the universe for the purposes of study, observation, and measurement. Theoretically, a system is isolated from its environment, but this is an artificial construct, since nothing is ever fully isolated. Earth is largely a closed system, meaning that it exchanges very little matter with its external environment in space, but the same is not true of the systems within the planet—geosphere, hydrosphere, biosphere, and atmosphere—which interact to such a degree that they are virtually inseparable. Together these systems constitute an intricate balance, a complex series of interrelations in which events in one sector exert a profound impact on conditions in another.

HOW IT WORKS

Systems

An isolated system is one so completely sealed off from its environment that neither matter nor energy passes through its boundaries. This is an imaginary construct, however, an idea rather than a reality, because it is impossible to create a situation in which no energy is exchanged between the system and the environment. Under the right conditions it is perhaps conceivable that matter could be sealed out so completely that not even an atom could pass through a barrier, but some transfer of energy is inevitable. The reason is that electromagnetic energy, such as that emitted by the Sun, requires no material medium in which to travel.

In contrast to an isolated system is a closed system, of which Earth is an approximation. Despite its name, a closed system permits the exchange of energy with the environment but does not allow matter to pass back and forth between the external environment and the system. Thus, Earth absorbs electromagnetic energy, radiated from the Sun, yet very little matter enters or departs Earth's system. Note that Earth is an *approximation* of a closed system: actually, some matter does pass from space into the atmosphere and vice versa. The planet loses traces of hydrogen in the extremities of its upper atmosphere, while meteorites and other forms of matter from space may reach Earth's surface.

Earth more closely resembles a closed system than it does an open one—that is, a system that allows the full and free exchange of both matter and energy with its environment. The human circulatory system is an example of an open system, as are the various "spheres" of Earth (geosphere, hydrosphere, biosphere, and atmosphere) discussed later. Whereas an isolated system is imaginary in the sense that it does not exist, sometimes a different feat of imagination is required to visualize an open system. It is intricately tied to its environment, and therefore the concept of an open system as a separate entity sometimes requires some imagination.

Using Systems in Science

To gain perspective on the use of systems in science as well as the necessity of mentally separating an open system from its environment, consider how these ideas are used in formulating problems and illustrating scientific principles. For example, to illustrate the principle of potential and kinetic energy in physics, teachers often use the example of a baseball dropping from a

great height (say, the top of a building) to the ground.

At the top of the building, the ball's potential energy, or the energy it possesses by virtue of its position, is at a maximum, while its kinetic energy (the energy it possesses by virtue of its motion) is equal to zero. Once it is dropped, its potential energy begins to decrease, and its kinetic energy to increase. Halfway through the ball's descent to the ground, its potential and kinetic energy will be equal. As it continues to fall, the potential energy keeps decreasing while the kinetic energy increases until, in the instant it strikes the ground, kinetic energy is at a maximum and potential energy equals zero.

KEEPING OUT IRRELEVANT DETAILS. What has been described here is a system. The ball itself has neither potential nor kinetic energy; rather, energy is in the system, which involves the ball, the height through which it is dropped, and the point at which it comes to a stop. Furthermore, because this system is concerned with potential and kinetic energy only in very simple terms, we have mentally separated it from its environment, treating it as though it were closed or even isolated, though in reality it would more likely be an open system.

In the real world, a baseball dropping off the top of a building and hitting the ground could be affected by such conditions as prevailing winds. These possibilities, however, are not important for the purposes of illustrating potential and kinetic energy, and even if they were, they could be incorporated into the larger energy system.

THE "MAGIC" OF A SYSTEM. Since kinetic energy and potential energy are inversely related, the potential energy at the top of the building will always equal the kinetic energy at the point of maximum speed, just before impact. This is true whether the ball is dropped from 10 ft. (3 m) or 1,000 ft. (305 m). It may seem almost magical that the sum of potential and kinetic energy is always the same or that the two values are perfectly inverse. In fact, there is nothing magical here: the system has a certain total energy, and this does not change, though the distribution of that energy can and does vary.

Suppose one had a money jar known to contain $20. If one reaches in and grasps a five-dollar bill, two one-dollar bills, three quarters, a dime, and two nickels ($7.95), there must be $12.05 left in the jar. There is nothing magical in this; rather, what has been illustrated is the physical principle of conservation. In physics and other sciences, "to conserve" something means "to result in no net loss of" that particular component. It is possible that within a given system, the component may change form or position, but as long as the net value of the component remains the same, it has been conserved. Thus, the total energy is conserved in the situation involving the baseball, and the total amount of money is conserved in the money-jar.

Applying the System Principle to Earth

In the baseball illustration, the distribution between types of energy varies, but the total amount is always the same. Likewise in the money-jar illustration, the total amount of money remains fixed even though the distribution according to various denominations may vary. The same is true of Earth, though here it is the total amount of matter. This includes valuable resources, among them materials that can be mined to produce energy—for instance, fossil fuels such as coal or petroleum—as well as waste products. Because Earth is a closed system, there are no additional resources, nor is there any dumping ground other than the one beneath our feet. Thus, the situation calls for prudence both in the use of the planet's material wealth and in the processing of materials that will leave a by-product of waste.

The fact that a closed system is by definition finite leads to the principle that the relationships between its constituent parts are likewise finite, and therefore changes in one part of the system are liable to produce effects in another part. Conditions in the baseball or money-jar illustrations are so simple that it is easy to predict the effect of a change. For instance, if we substitute a basketball for a baseball, this will change the total energy, because the latter is a function of the ball's mass. If the denominations making up the $20 in the money jar are replaced with a collection of two-dollar bills and dimes, this will make it impossible to reach in and pull out an odd-numbered value in dollars or cents.

What about the changes that result when one aspect of Earth's system is altered? In some cases, it is easy to guess; in others, the interactions are so complex that prediction requires sophisticated mathematical models. It is perhaps

no accident that chaos theory was developed by a meteorologist, the American Edward Lorenz (1917–). Chaos theory, the study of complex systems that appear to follow no orderly laws, involves the analysis of phenomena that appear connected by something than an ordinary cause and effect relationship. The classic example of this is the "butterfly effect," the idea that a butterfly beating its wings in China can change the weather in New York City. This, of course, is a far-fetched scenario, but sometimes changes in one sector of Earth's system can yield amazing consequences in an entirely different part.

THE FOUR "SPHERES"

The systems approach is relatively new to the earth sciences, themselves a group of disciplines whose diversity reflects the breadth of possible approaches to studying Earth (see Studying Earth). At one time, earth scientists tended to investigate specific aspects of Earth without recognizing the ways in which these aspects connect with one another; today, by contrast, the paradigm of the earth sciences favors an approach that incorporates the larger background.

Given the complexities of Earth itself, as well as the earth sciences, it is helpful to apply a schema (that is, an organizational system) for dividing larger concepts and entities into smaller ones. For this reason, earth scientists tend to view Earth in terms of four interconnected "spheres." One of these terms, atmosphere, is a familiar one, while the other three (geosphere, hydrosphere, and biosphere) may sound at first like mere scientific jargon.

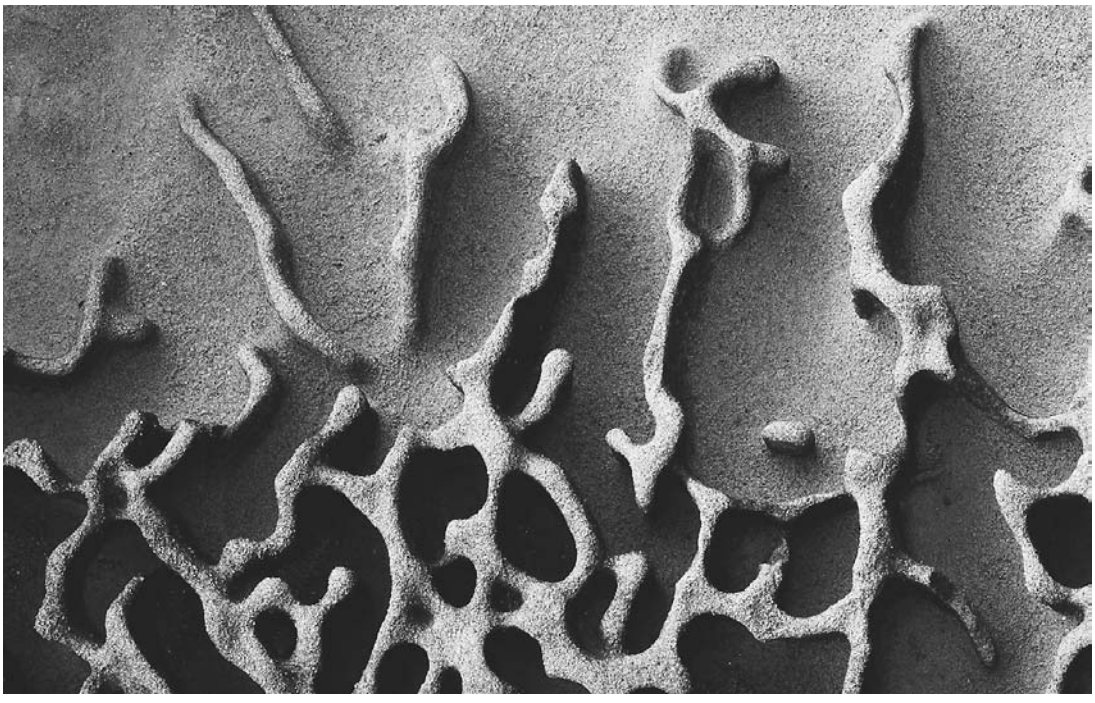
UNDERSTANDING THE SPHERES. In fact, each sphere represents a sector of existence on the planet that is at once clearly defined and virtually inseparable from the others. Each is an open system within the closed system of Earth, and overlap is inevitable. For example, the seeds of a plant (biosphere) are placed in the ground (geosphere), from which they receive nutrients for growth. In order to sustain life, they receive water (hydrosphere) and carbon dioxide (atmosphere). Nor are they merely receiving: they also give back oxygen to the atmosphere, and by providing nutrition to an animal, they contribute to the biosphere.

Each of the spheres, or Earth systems, is treated in various essays within this book. These essays examine these subsystems of the larger Earth system in much greater depth; what follows, by contrast, is the most cursory of introductions. It should be noted also that while these four subsystems constitute the entirety of Earth as humans know and experience it, they are only a small part of the planet's entire mass. The majority of that mass lies below the geosphere, in the region of the mantle and core.

A CURIOUS AND INSTRUCTIVE POINT. As a passing curiosity, it is interesting to note that modern scientists have identified four subsystems and given them the name spheres. As discussed in the essay Earth, Science, and Nonscience, the ancient Greeks were inclined to divide natural phenomena into fours, a practice that reached its fullest expression in the model of the universe developed by the Greek philosopher Aristotle (384–322 B.C.) He even depicted the physical world as a set of spheres and suggested that the heaviest material would sink to the interior of Earth while the lightest would rise to the highest points.

These points of continuity with ancient science are notable because almost everything about Aristotle's system was wrong, and, indeed, the differences between his model of the physical world and the modern one are instructive. There are four spheres in the modern earth sciences because these four happen to be useful ways of discussing the larger Earth system—not, as in the case of the Greeks, because the number four represents spiritual perfection. Furthermore, scientists understand these spheres to be artificial constructs, at least to some extent, rather than a key to some deeper objective reality about existence, as the ancients would have supposed.

Nor are the spheres of the modern earth sciences literally spheres, as Aristotle's concentric orbits of the planets around Earth were. If anything, the use of the term sphere represents a holdover from the Greek way of viewing the material world. Finally, unlike such ancient notions as the concept of the four elements, four qualities, or four humors, the idea of the four spheres is not simply the result of pure conjecture. Instead, the concept of these four interrelated systems came about by application of the scientific method and entered the vocabulary of earth scientists because the ideas involved clearly reflected and illustrated the realities of Earth processes.



Sandstone eroded by waves. *(© Stephen Parker/Photo Researchers. Reproduced by permission.)*

The Spheres in Brief

The geosphere itself may be defined as the upper part of the planet's continental crust, the portion of the solid earth on which human beings live, which provides them with most of their food and natural resources. Even with the exclusion of the mantle and core, the solid earth portion of Earth's system is still by far the most massive. It is estimated that the continental and oceanic crust to a depth of about 1.24 mi. (2 km) weighs 6×10^{21} kg—about 13,300 billion billion pounds. The mass of the biosphere, by contrast, is about one millionth that figure. If the mass of all four spheres were combined, the geosphere would account for 81.57%, the hydrosphere 18.35%, the atmosphere 0.08%, and the biosphere a measly 0.00008%. (Of that last figure, incidentally, animal life—of which humans are, of course, a very small part—accounts for less than 2%.)

Not only is the geosphere the largest, it is also by far the oldest of the spheres. Its formation dates back about four billion years, or within about 0.5 billion years of the planet's formation. As Earth cooled after being formed from the gases surrounding the newborn Sun, its components began to separate according to density. The heaviest elements, such as iron and nickel, drifted toward the core, while silicon rose to the surface to form the geosphere.

Atmosphere, hydrosphere, and biosphere. In that distant time Earth had an atmosphere in the sense that there was a blanket of gases surrounding the planet, but the atmospheric composition was quite different from today's mixture of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon, which together comprise 0.07%. The atmosphere then consisted largely of carbon dioxide from Earth's interior as well as gases brought to Earth by comets. Elemental hydrogen and helium escaped the planet, and much of the carbon was deposited in what became known as carbonate rocks. What remained was a combination of hydrogen compounds, including methane, ammonia, nitrogen- and sulfur-rich compounds expelled by volcanoes, and (most important of all) H_2O, or water.

Simultaneous with these developments, the gases of Earth's atmosphere cooled and condensed, taking the form of rains that, over millions of years, collected in deep depressions on the planet's surface. This was the beginning of the oceans, the largest but far from the only component of Earth's hydrosphere, which consists of

all the planet's water except for water vapor in the atmosphere. Thus, the hydrosphere includes not only saltwater but also lakes, streams, groundwater, snow, and ice.

Water, of course, is necessary to life, and it was only after its widespread appearance that the first life-forms appeared. This was the beginning of the biosphere, which consists of all living organisms as well as any formerly living material that has not yet decomposed. (Typically, following decomposition an organism becomes part of the geosphere.) Over millions of years, plants formed, and these plants gradually began producing oxygen, helping to create the atmosphere as it is known today—an example of interaction between the open systems that make up the larger Earth system.

REAL-LIFE APPLICATIONS

Earth As an Organism

Clearly, a great deal of interaction occurs between spheres and has continued to take place for a long time. Earth often is described as a living organism, a concept formalized in the 1970s by the English meteorologist James Lovelock (1919–) and the American biologist Lynn Margulis (1938–), who developed the Gaia hypothesis. Sometimes called the Gaian hypothesis, this principle is named after the Greek earth goddess, a prototype for "Mother Earth," and is based on the idea that Earth possesses homeostatic or self-regulating mechanisms that preserve life. (Lovelock's neighbor William Golding [1911–1993], author of *Lord of the Flies,* suggested the name to him.)

Though the Gaia hypothesis seems very modern and even a bit "New Age" (that is, relating to a late twentieth-century movement that incorporates such themes as concern for nature and spirituality), it has roots in the ideas of the great Scottish geologist James Hutton (1726–1797), who described Earth as a "superorganism." A forward-thinking person, Hutton maintained that physiology provides the model for the study of Earth systems. Out of Hutton's and, later, Lovelock's ideas ultimately grew the earth science specialty of geophysiology, an interdisciplinary approach incorporating aspects of geochemistry, biology, and other areas.

The Gaia hypothesis is far from universally accepted, however, and remains controversial. One reason is that it seems to contain a teleologic, or goal-oriented, explanation of physical behaviors that does not fully comport with the findings of science. An animal responds to external conditions in such a way as to preserve life, but this is because it has instinctive responses "hardwired" into its brain. Clearly, if the Earth is an "organism, " it is an organism in quite a different sense than an animal, since it does not make sense to describe Earth as having a "brain."

Homeostasis and Cycles

Nonetheless, Lovelock, Margulis, and other supporters of the Gaia hypothesis have pointed to a number of anomalies that have yet to be explained fully and for which the Gaia hypothesis offers one possible solution. For example, it would have taken only about 80 million years for the present levels of salt in Earth's oceans to have been deposited there from the geosphere; why, then, is the sea not many, many times more salty than it is? Could it be that Earth has somehow regulated the salinity levels in its own seas?

Earth's systems unquestionably display a homeostatic and cyclical behavior typical of living organisms. Just as the human body tends to correct any stresses imposed on it, Earth likewise seeks equilibrium. And just as blood, for instance, cycles through the body's circulatory system, so matter and energy move between various spheres in the course of completing certain cycles of the Earth system. These include the energy and hydrologic cycles; a number of biogeochemical cycles, such as the carbon and nitrogen cycles; and a rock cycle of erosion, weathering, and buildup. (Each of these systems is discussed in a separate essay, or as part of a separate essay, in this book.)

FEEDBACK. Though particulars of the Gaia hypothesis remain a matter of question, it is clear that Earth regulates these cycles and does so through a process of feedback and corrections. To appreciate the idea of feedback, consider a financial example. In the early 1990s, the U.S. Congress placed a steep tax on luxury boats, presumably with the aim of getting more money from wealthy taxpayers. The result, however, was exactly the opposite: boat owners sold their crafts, and many of those considering purchases cancelled their plans. Rather than redistributing



An oil-covered bird, victim of the 1989 Exxon Valdez's oil spill in Prince William Sound, Alaska. *(AP/Wide World Photos. Reproduced by permission.)*

wealth from the rich to those less fortunate, the tax resulted in the government's actually getting *less* money from rich yacht owners.

Whereas Congress expected the rich to provide positive feedback by giving up more tax money, instead the yacht owners responded by acting against the tax—a phenomenon known as negative feedback. Feedback itself is the return of output to a system, such that it becomes input which then produces further output. Feedback that causes the system to move in a direction opposite that of the input is negative feedback, whereas positive feedback is that which causes the system to move in the same direction as the input. The luxury tax would have made perfect sense if the purpose had been to halt the production and purchase of expensive boats, in which case the output would have been deemed positive.

In the luxury-tax illustration, negative feedback is truly "negative" in the more common sense of the word, but this is not typically the case where nature in general or Earth systems in particular are concerned. In natural systems negative feedback serves as a healthy corrective and tends to stabilize a system. To use an example from physiology, if a person goes into a cold environment, the body responds by raising the internal temperature. Likewise, in chemical reactions the system tends to respond to any stress placed on it by reducing the impact of the stress, a concept known as Le Châtelier's principle after the French chemist Henry Le Châtelier (1850–36).

Positive feedback, on the other hand, is often far from "positive" and is sometimes described as a "vicious cycle." Suppose rainwater erodes a portion of a hillside, creating a gully. Assuming the rains continue, the opening of this channel for the water facilitates the introduction of more water and therefore further erosion of the hillside. Given enough time, the rain can wash a deep gash into the hill or even wash away the hill entirely.

Far-Reaching Consequences

Given the interconnectedness of systems on Earth, it is easy to see how changes in one part of the larger Earth system can have far-reaching impacts on another sector. For example, the devastating Alaska earthquake of March 1964 produced tsunamis felt as far away as Hawaii, while the Exxon *Valdez* oil spill that afflicted Alaska exactly 25 years later had an effect on the biosphere and hydrosphere over an enormous area.

El Niño is a familiar example of far-reaching consequences produced by changes in Earth sys-

KEY TERMS

ATMOSPHERE: A blanket of gases surrounding Earth and consisting of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon, which together comprise 0.07%.

BIOSPHERE: A combination of all living things on Earth—plants, mammals, birds, reptiles, amphibians, aquatic life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed. Typically, after decomposing, a formerly living organism becomes part of the geosphere.

CLOSED SYSTEM: A system that permits the exchange of energy with its external environment but does not allow matter to pass between the environment and the system. Compare with isolated system, on the one hand, and open system, on the other.

CONSERVATION: In physics and other sciences, "to conserve" something means "to result in no net loss of" that particular component. It is possible that within a given system, the component may change form or position, but as long as the net value of the component remains the same, it has been conserved.

ELECTROMAGNETIC ENERGY: A form of energy with electric and magnetic components, which travels in waves and, depending on the frequency and energy level, can take the form of long-wave and short-wave radio; microwaves; infrared, visible, and ultraviolet light; x rays; and gamma rays.

ENVIRONMENT: In discussing systems, the term *environment* refers to the surroundings—everything external to and separate from the system.

FEEDBACK: The return of output to a system, such that the output becomes input that produces further output. Feedback that causes the system to move in a direction opposite to that of the input is negative feedback, whereas positive feedback is that which causes the system to move in the same direction as the input.

GAIA HYPOTHESIS: The concept, introduced in the 1970s, that Earth behaves much like a living organism, possessing self-regulating mechanisms that preserve life. Sometimes called the Gaian hypothesis, it is named after Gaia, the Greek goddess of the earth.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

HOMEOSTASIS: A tendency toward equilibrium.

HOMEOSTATIC: The quality of being self-regulating.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

ISOLATED SYSTEM: A system that is so fully separated from the rest of the universe that it exchanges neither matter nor energy with its environment. This is an imaginary construct, since full isolation is impossible.

OPEN SYSTEM: A system that allows complete, or near-complete, exchange of matter and energy with its environment.

KEY TERMS CONTINUED

SCIENTIFIC METHOD: A set of principles and procedures for systematic study that includes observation; the formation of hypotheses, theories, and laws; and continual testing and reexamination.

SYSTEM: Any set of interactions that can be set apart mentally from the rest of the universe for the purposes of study, observation, and measurement.

TSUNAMI: A tidal wave produced by an earthquake or volcanic eruption. The term comes from the Japanese words for "harbor" and "wave."

tems. Spanish for "child" (because it typically occurs around Christmastime), El Niño begins on the western coast of South America. There, every few years, trade winds slacken, allowing the wind from the west to push warm surface water eastward. Lacking vital nutrients, this warm water brings about a decline in the local marine life. It also causes heavy rains and storms.

IMPACT OF EL NIÑO AROUND THE WORLD. To the extent described, El Niño is largely a local phenomenon. But it can affect the jet streams, or high-level winds, that push storms across the Western Hemisphere. This can result in milder weather for western Canada or the northern United States, as the winds push more severe storms into Alaska, but it also can bring about heavy rains in the Gulf of Mexico region. Nor are its effects limited to the Western Hemisphere. El Niño has been known to alter the pattern of monsoons, or rainy seasons, in India, Southeast Asia, and parts of Africa, thus producing crop failures that affect millions of people.

Aside from the indirect effects, such as the famines in the Eastern Hemisphere, the direct effects of the El Niño phenomenon can be devastating. The El Niño of 1982–83, which affected the United States, the Caribbean, western South America, Africa, and Australia, claimed some 2,000 lives and cost about $13 billion in property damage. It returned with a vengeance 15 years later, in 1997–98, killing more than 2,100 people and destroying $33 billion worth of property.

Years Without Summer

Whereas El Niño is an example of a disturbance in the hydrosphere that affects the atmosphere and ultimately the biosphere, an even more terrifying phenomenon can begin with an eruption in the geosphere, which spreads to the atmosphere and then the hydrosphere and biosphere. This phenomenon might be called "years without summer"; an example occurred in 1815–16.

In June of 1816 snow fell in New England, and throughout July and August temperatures hovered close to freezing. Frosts hit in September, and New Englanders braced themselves for an uncommonly cold winter, as that of 1816–17 turned out to be. It must have seemed as though the world were coming to an end, yet the summer of 1817 proved to be a normal one. The cause behind this year without summer in 1816 lay in what is now Indonesia, and it began a year earlier.

In 1815, Mount Tambora to the east of Java had erupted, pouring so much volcanic ash into the sky that it served as a curtain against the Sun's rays, causing a brutally cold summer in New England the following year. An eruption of Mount Katmai in Alaska in 1912 produced far-reaching effects, including some lowering of temperatures, but its impact was nothing like that of Tambora. Nor did the 1980 Mount Saint Helens eruption in Washington State prove nearly as potent in the long run as the eruption of Tambora did (though it produced a devastating immediate impact).

THE CATACLYSM OF A.D. 535. Even the eruption of Mount Tambora may have been overshadowed by another, similar event, known simply as the catastrophe, or cataclysm, of A.D. 535. In the late twentieth century, the British dendrochronologist Mike Baillie discovered a pattern of severely curtailed growth in tree rings dating to the period A.D. 535–541. More or less

simultaneous with Baillie's work was that of the amateur archaeologist David Keys, who found a number of historical texts by Byzantine, Chinese, and Anglo-Saxon scholars of the era, all suggesting that something cataclysmic had happened in A.D. 535. For example, the Byzantine historian Procopius (d. 565) wrote, "The sun gave forth its light without brightness ... for the whole year."

Some geologists have maintained that the cataclysm resulted from the eruption of another Indonesian volcano, the infamous Krakatau, which had a devastating eruption in 1883 and which could have produced enough dust to cause an artificial winter. Whatever the cause, the cataclysm had an enormous impact that redounds from that time perhaps up to the present. The temperature drop may have sparked a chain of events, beginning in southern Africa, that ultimately brought a plague to the Byzantine Empire, forcing Justinian I (r. A.D. 483–565) to halt his attempted reconquest of western Europe. At the same time, the cataclysm may have been responsible for food shortages in central Asia, which spawned a new wave of European invasions, this time led by the Avars.

The result was that the fate of Europe was sealed. For a few years it had seemed that Justinian could reconquer Italy, thus reuniting the Roman Empire, whose western portion had ceased to exist in A.D. 476. Forced to give up their reconquest, with the Avars and others overrunning Europe while the plague swept through Greece, the Byzantines turned their attention to affairs at home and increasingly shut themselves off from western Europe. Thus the Dark Ages, the split between Catholicism and Eastern Orthodoxy, the Crusades—even the Cold War, which reflected the old east-west split in Europe—may have been the results of a volcano on the other side of the world.

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THE STUDY OF EARTH

STUDYING EARTH

MEASURING AND MAPPING EARTH

REMOTE SENSING

STUDYING EARTH

CONCEPT

The physical sciences include astronomy, physics, chemistry, and the earth sciences, but the last of these sciences is quite unlike the other three. Whereas the objects of study in physics and chemistry often seem abstract to the uninitiated and astronomy is concerned with faraway planets and other bodies, the earth sciences are devoted to things that are both concrete and immediate. The focus of study for the earth sciences is literally underneath our feet, a planet at once vast and tiny, a world that (as far as we know) stands alone in the universe as the sole supporter of intelligent life. The earth sciences also differ from other disciplines in that their boundaries are not always defined clearly. The study of Earth is a multifarious array of specialties that includes a range of geologic, hydrologic, and atmospheric sciences that overlap with the other physical sciences, biology, and even the social sciences.

HOW IT WORKS

Introduction to the Earth Sciences

At the simplest level, the earth sciences can be divided into three broad areas: the geologic, hydrologic, and atmospheric sciences. These specialties fit neatly with three of the "spheres," or subsystems within the larger Earth system: geosphere, hydrosphere, and atmosphere. (See Earth Systems for more about the spheres.) The fourth of these subsystems is the biosphere, and this illustrates the difficulty of stating exactly what is and what is not a part of the earth sciences.

Usually the earth sciences are considered part of the physical sciences, as opposed to the biological sciences, such as biology, botany, and zoology. Yet the earth sciences clearly overlap with biological sciences in a variety of areas, such as oceanography and various studies of complex biological environments. There is even a new (and as yet not fully formalized) discipline called geophysiology, built on the premise that Earth has characteristics of a living organism.

Overlap with other physical sciences. The earth sciences also overlap with other physical sciences in several realms. There is geophysics, which addresses the planet's physical processes, including its magnetic and electric properties and the means by which energy is transmitted through its interior. There is also geochemistry, which is concerned with the chemical properties and processes of Earth. And there are numerous areas of confluence between the earth sciences and astronomy (among them, planetary geology), which fall under the heading of planetary science (sometimes called planetology or planetary studies).

These terms all refer to the same discipline, a branch of the earth sciences concerned with the study of other planetary bodies. This discipline, or set of disciplines, is concerned with the geologic, geophysical, and geochemical properties of other planets but also draws on aspects of astronomy, such as cosmology. Regardless of the name by which it is called, planetology is an example of the fact that the study of Earth is still very much an evolving set of disciplines. In many cases, the earth sciences are still in process of being defined.

Scientific Paradigms

This last point is an important one to consider because of what it implies about the nature of scientific study. In the past, scientists tended to think that they were in the business of discovering some sort of objective truth that was waiting for them to discover it; in reality, however, the quest of the scientific thinker is much less guided. The natural world does not in any way speak to the scientist, telling him or her how to categorize data. In fact, the divisions of scientific knowledge with which we are familiar have come about not because they necessarily reflect an underlying truth, but because they have proved useful in separating certain aspects of the physical world from certain others.

When science had its beginnings in ancient times, scientists were simply collecting observations (including a lot of incorrect ones) and sometimes forming theories of a sort, but they did not think in terms of developing models for viewing their objects of study. Today, however, scientific thinkers are acutely conscious of the model, or paradigm, that governs a particular discipline, school of thought, or theory.

A paradigm may be likened to a lens. The lens does not change the actual object that is viewed through it; it can alter only the way in which it is viewed. As thinkers within a particular discipline or theory begin to define the governing paradigm, they are much like an eye doctor testing various lenses on a patient. In such a situation, there is no one lens that is right for all circumstances. Rather, it is a question of finding the lens that best suits the patient's vision needs.

All sciences are gradually changing, evolving models that better suit the data under their consideration. Chemistry, for instance, was once primarily a matter simply of mixing chemicals and observing their external processes. In fact, the definition of chemistry has expanded greatly since about 1800, and today it is more like what people tend to think of as physics; that is, it is concerned with atomic and subatomic structures and types of behavior. The earth sciences are in an even more transitional state, and the problem of defining the disciplines it comprises is a still more fundamental one.

The evolving earth sciences. In the discussion that follows, we outline the broad parameters of the earth sciences, considering basic areas of study and specialties within them. This does not represent a definitive organizational scheme, nor does this brief review refer to every possible area of study in the wide-ranging earth sciences. To do so would require an entire book; rather, the purpose is to consider the most significant disciplines and subdisciplines.

To appreciate the way that these disciplines fit within the larger perspective, however, it is necessary to examine a few historical details. Most of these details concern the early history of the earth sciences, since much of the more modern history (for example, the development of plate tectonics theory during the 1960s) is treated in the relevant essays within this book. The purpose of this brief historical review, instead, is to impart an understanding about how the study of Earth emerged as a real science, as opposed to a merely descriptive undertaking concerned with recording observations. Important themes are the development of the scientific method as well as the search for proper ways of classifying the various studies under the heading of what became known as the earth sciences.

Real-Life Applications

The Scientific Method

As discussed later, the scientific method emerged during the seventeenth century and has remained in use ever since. It is a way of looking at facts and data, and its application is what truly separates science from nonscience. Nonscientific "theories" postulate answers based not on evidence but on pure conjecture, a habit of mind that was widespread before the development of the scientific method and is still all too common. A contemporary example would be the claim that intelligent extraterrestrial life-forms built the great pyramids of Egypt.

The only real basis for this belief is the fact that the pyramids are extremely sophisticated architectural achievements for a civilization that had no metal tools, no wheel, and virtually no understanding of geometry, as was the case in Egypt in about 2500 B.C. But is a huge conceptual leap to go from the observation of these anomalies to the claim that visitors from outer space built the pyramids. The same is true of other strange artifacts from ancient or prehistoric

times, such as the great structures of Stonehenge in England or the Nazca lines in South America. They are curious, puzzling, and intriguing, and it may be fun to speculate about engineers from another world—but such speculation is *not* science. (For more about the methodological distinctions between science and its opposite, see Earth, Science, and Nonscience.)

It is no mistake that here we are talking about the application of the scientific method to something outside the "hard sciences," the study of the pyramids being the province of social sciences, such as archaeology and history. In fact, the method has had just as much impact in those areas as it has in the physical and biological sciences. The scientific method (along with the closely related philosophical principles of basic logic, handed down from the ancient Greeks) can be applied in many aspects of daily life, enabling a person to make sense of a complex world. Many of the controversies of the modern world, including those involving race, sex, religion, and politics, could be treated more constructively if people approached the topics with a genuine interest in understanding the facts rather than simply finding confirmation for their emotionally based preconceived notions.

APPLYING THE SCIENTIFIC METHOD. Scientists rigorously applying the scientific method begin their quest for understanding by looking solely at the facts that can be garnered by observation. On the basis of these data, they form hypotheses, or unproven statements regarding observed phenomena. This is usually as far as many people go in their thinking, and it is not far enough: up to this point, for instance, the theory that claims that visitors from another planet built the pyramids is in accordance with the scientific method. But such fanciful notions, as well as kindred ideas, such as conspiracy theories, never go to the next step, which marks the dividing line between science and pure opinion.

Having formed a hypothesis, the scientist subjects it to testing, the most critical component of the scientific method. By contrast, advocates of nonscientific ideas (which, of course, usually pose as scientific ideas) typically focus on searching for evidence that will confirm the hypothesis. Anything that supports the hypothesis is reported; anything that does not is simply ignored. By contrast, a true scientist is constantly trying to *disprove* his or her own hypotheses.



Nicolaus Copernicus *(Library of Congress.)*

If a hypothesis withstands enough repeated testing, it acquires the status of a theory, or a more general statement about nature. If the idea embodied in a theory is shown to be the case in every situation for which it is tested, it then becomes a law. The process is a bit like that involved in making metal stronger: the more abuse it endures, assuming it is able to recover, the more impervious it will be to further abuse. But every type of metal has its limits, a threshold of compression or tension beyond which it cannot retain its original shape, and likewise it is possible that a scientific law can be overturned. For this reason, all laws are subject to continual testing, and if a test disproves a scientific law, this opens the way for the development of a new paradigm.

The Historical Roots of the Earth Sciences

The earth sciences are both old and new. On the one hand, they address matters of fundamental importance to human beings, and for this reason, the rudiments of the earth sciences probably made their appearance before any of the other fields of scientific study except perhaps astrono-

my. From prehistoric times, societies have been concerned with obtaining metals from the ground to make tools and weapons, finding water to support human life and crops, and discerning the future of weather patterns that could greatly affect conditions for human populations. Thus were born, respectively, the geologic, hydrologic, and atmospheric sciences.

Much of what took place in the earth sciences before about 1800, however, was a matter of superstition, legend, guesswork, and a smattering of real science. Much of it was dominated by religious belief, which relied on a strict interpretation of the Bible. Based on the amount of time that elapsed between Adam and Jesus, combined with the fact that Genesis 1 states that Adam was created at the end of the first week of Earth's existence, the Catholic Church maintained that the planet could not possibly be more than a few thousand years old. (For more on this subject, see Earth, Science, and Nonscience.)

THE ANCIENT EARTH SCIENCES. Despite the many impediments to scientific study in ancient times, a few thinkers contributed significantly to our knowledge. For instance, the Greek philosopher Aristotle (384–322 B.C.) discovered that Earth is a sphere by noting the rounded shadow on the Moon during a lunar eclipse. His pupil, Theophrastus (372?–287? B.C.), wrote a highly competent work, *Concerning Stones,* that remained a guide to mineralogy for two millennia. A few centuries later, the Greek mathematician Eratosthenes of Cyrene (*ca.* 276–*ca.* 194 B.C.) made an astoundingly accurate measurement of Earth's circumference.

Much of what passed for science, however, was little more than entertaining, anecdotal misinformation. Such is the case, for instance, in the *Historia Naturalis* (Natural history) of the Roman scholar Pliny the Elder (A.D. 23–79), a work that, despite its many flaws, remained widely respected through the Renaissance. As for Eratosthenes' measurement of Earth, the Alexandrian astronomer Ptolemy (*ca.* A.D. 100–170) rejected it in favor of a much smaller, much less correct figure. Thus, Ptolemy may deserve some of the credit for discovering the New World: if Christopher Columbus (1451–1506) had known just how far it was around Earth, he might not have been so confident about sailing off into the seas to the west of Europe.

Ptolemy's rejection of Eratosthenes's measurement was far from his only negative contribution to the history of science. Influenced by highly misguided concepts handed down from Aristotle himself (see Earth, Science, and Nonscience), he developed a complex cosmology that depicted Earth as the center of the universe. By this he meant that Earth was the center of the solar system, because up until a few centuries ago, astronomers believed that space consisted only of Earth, Sun, Moon, the five planets visible to the naked eye, and the "fixed stars" in the night sky.

DAWN OF THE SCIENTIFIC METHOD. What made Ptolemy's cosmology so complex, of course, was the fact that Earth is not anywhere near the center of the universe, and therefore his system required intricate mathematical acrobatics to remain workable. This posed little problem during the early Middle Ages, when learning in Europe all but ceased, and even in the much more scientifically progressive Muslim world of that time, Ptolemy's word remained virtual holy writ. By the late Middle Ages, however, as scientific learning returned to Europe, thinkers began to notice increasing difficulties in using his system.

The watershed event in what became known as the Scientific Revolution was the proof, by the Polish astronomer Nicolaus Copernicus (1473–1543), that Earth and the other planets of the solar system revolve around the Sun. By that point, the Catholic Church had given its official approval to Ptolemy's geocentric model, because it comported well with the idea that God had created humankind in his own image to fulfill a specific destiny. Therefore, Copernicus's challenge to established teachings proved highly controversial, and the Italian astronomer Galileo Galilei (1564–1642) would be forced to recant his support of it or face punishment by death.

Yet Galileo paved the way for the full acceptance of Copernicus's work and for the Scientific Revolution that followed in its wake. His theories and experiments concerning gravitational acceleration greatly influenced the English natural philosopher Isaac Newton (1642–1727), leading to the latter's epochal work on gravitation and motion. But at least as important as Galileo's work was his methodology: Galileo virtually introduced the scientific method, providing a set of principles for systematic study.

The Foundations of Modern Geology

The scientific method had an enormous impact on all the sciences. Unlike earlier "scientific" principles, which were built on the teachings of religious prophets or the uninformed conjecture of philosophers, this one was established on a foundation of observation, and it opened the way for unprecedented progress in the sciences.

Until late in the eighteenth century, however, the relatively young field of geology centered primarily on mere observation rather than the development of theories. Thus, the discipline was not all that different from what it had been in ancient times, or when the Anglo-Saxon historian known as the Venerable Bede (673–735) coined the term geology. The latter term, a combination of the Greek *geo* and *logia,* means "study of Earth," and was intended to distinguish such pursuits from theology, or the study of heavenly things.

Historical and physical geology. In modern times, geology is defined as the study of the solid earth, in particular, its rocks, minerals, fossils, and land formations. As for Bede's putative opposition between geology and theology, it would become more pronounced in the period from about 1500 to 1800, as the findings of geologists began increasingly to contradict the teachings in the biblical book of Genesis. Among the first to consider the age of Earth in scientific terms, rather than by recourse to the Scriptures, was one of the world's greatest thinkers: the Italian scientist and artist Leonardo da Vinci (1452–1519), who speculated that fossils might have been made by the remains of long-dead animals.

Less famous was Leonardo's German contemporary Georgius Agricola (1494–1555), the "father of mineralogy," who wrote extensively on mining, metallurgy, and minerals. Together, these two men represent the two principal strains of geology: historical geology, or the study of Earth's history, and physical geology. The latter discipline, of which Agricola was a key representative, is concerned with the material components of Earth and with the forces that have shaped the planet. All the areas of geology discussed here fall under one of those two headings.

Most of the important developments in geology during the period from 1500 to 1800 fall under the heading of historical geology, beginning with a key observation on strata, or layers of rock, made by the Danish geologist Nicolaus Steno (1638–1687). As Steno correctly hypothesized, the lower a layer of rock lies, the earlier the historical period it represents. These observations, later developed into a theory by the German geologist Johann Gottlob Lehmann (1719–1767), had several implications.

First of all, the ideas of Steno and Lehmann provided geologists with a method for dating the age of rock formations not unlike the rings observed by dendrochronologists studying the biography of a tree. As a result of study based on these findings, scientists were confronted with the growing realization that Earth is much, much older than a strict interpretation of the Bible would suggest. This finding, in turn, led to the first theories concerning the shaping of Earth and thus to the foundation of geology as a modern scientific discipline.

Three important schools of thought. In the wake of this breakthrough, at least three schools of thought developed. One of them, catastrophism, centered around the foregone conclusion that Earth had been created in six literal days or, at the very least, in an extremely short time, through a series of catastrophes. Opposed to this view was the Neptunist stratigraphy of the German geologist Abraham Gottlob Werner (1750–1817), who maintained that Earth had been shaped by a vast ocean (hence the name *Neptune*) that once covered its entire surface. Finally, there was the Plutonist school of the Scottish geologist James Hutton (1726–1797). Named after the Greek god of the underworld, this theory held that volcanoes and other disturbances beneath Earth's surface had been the principal forces in shaping the planet.

Hutton's theory would prevail, and today he is regarded as the father of modern geology. In *Theory of the Earth* (1795), he introduced one of the key concepts underlying the study of the planet's history, the principle of uniformitarianism—the idea that the forces at work on Earth today have always been in operation and are the same ones that shaped it. Nonetheless, Neptunism and even catastrophism had their merits. Although Werner and his followers were incorrect, Neptunism was the first well-developed theory concerning Earth's origins and helped pave the way for others.

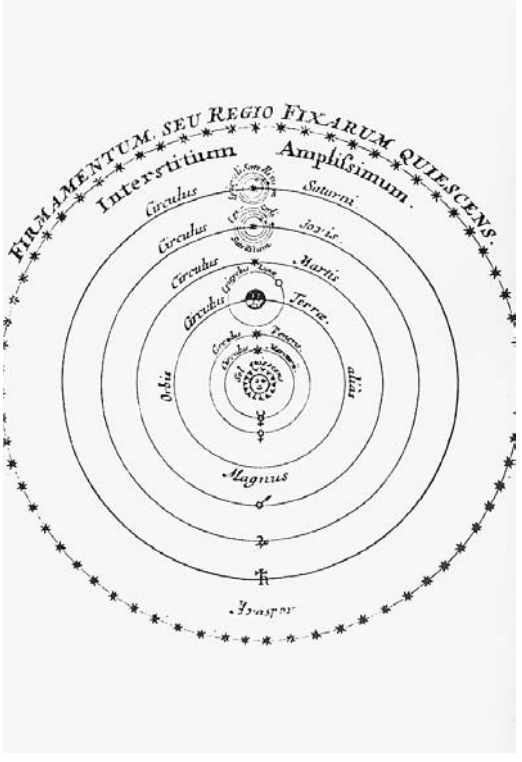


Diagram showing the solar system as Copernicus envisioned it, with the sun at the center. The Copernican system heralded the start of the Scientific Revolution. *(© Dr. Jeremy Burgess/Photo Researchers. Reproduced by permission.)*

As for the advocates of catastrophism, they were correct inasmuch as they noted the role of sudden catastrophes in shaping the planet. These catastrophes (for instance, a comet about 66 million years ago, which may have destroyed the dinosaurs), however, can be explained within the framework of a very old Earth. Nor does the fact of the catastrophes themselves in any way suggest a planet that is only a few thousand years old.

LATER DEVELOPMENTS. As noted earlier, the later history of the earth sciences is discussed more properly within the context of specific subjects. Instead, our focus here is on the array of disciplines that proliferated alongside geology and on the need for a disciplinary paradigm larger than that of geology alone. By the mid–twentieth century, the range of disciplines involved in the study of Earth had become so complex and varied that it was a major achievement when the English geologist Arthur Holmes (1890–1965) developed a model that incorporated most of them. Holmes's system was not simply a "model" in the way that the term typically is used; Holmes also constructed a literal diagram that enabled students to visualize the relationships between subdisciplines.

Holmes's model was concerned primarily with the solid earth sciences, or the geologic sciences, meaning that it did not include the hydrologic sciences. Within its purview, however, it used a method of classification so broad (yet still targeted) that it has been adapted in recent years to include subdisciplines developed since Holmes's time. These changes serve to emphasize further the evolving nature of what came to be known as the earth sciences. The latter term came into use only during the 1960s and 1970s, when it became apparent that neither geology alone nor even a combination of geology, geophysics, and geochemistry could encompass all the areas of study devoted to Earth.

Overview of the Earth Sciences

Throughout most of what remains of this essay, we very briefly sketch the outlines of the earth sciences. It should be reiterated that the organizational system used here is not necessarily definitive and is intended only to provide the reader with a general idea as to how the various earth sciences fit together.

GEOLOGY. At the core of the earth sciences, of course, is geology itself, which focuses on the study of the solid earth. As noted earlier, geology can be subdivided into historical and physical geology. The principle subdisciplines of historical geology are as follows.

- Stratigraphy: the study of rock layers, or strata, beneath Earth's surface
- Geochronology: the study of Earth's age and the dating of specific formations in terms of geologic time
- Sedimentology: the study and interpretation of sediments, including sedimentary processes and formations
- Paleontology: the study of fossilized plants and animals, or flora and fauna
- Paleoecology: the study of the relationship between prehistoric plants and animals and their environments.

Note that there are several other disciplines referred to by the prefix *paleo-* (or *palaeo-*), Greek for "very old." Two of the more well-known ones are paleobiology and paleobotany, but the subdisciplines can become very specialized, as evidenced by the existence of a field

KEY TERMS

BIOSPHERE: A combination of all living things on Earth—plants, mammals, birds, reptiles, amphibians, aquatic life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed. Typically, after decomposing, a formerly living organism becomes part of the geosphere.

COSMOLOGY: The study of the origin, structure, and evolution of the universe.

ECONOMIC GEOLOGY: The study of fuels, metals, and other materials from Earth that are of interest to industry or the economy in general.

GEOCENTRIC: Earth-centered.

GEOCHEMISTRY: A branch of the earth sciences, combining aspects of geology and chemistry, that is concerned with the chemical properties and processes of Earth.

GEOCHRONOLOGY: The study of Earth's age and the dating of specific formations in terms of geologic time.

GEOLOGY: The study of the solid earth, in particular, its rocks, minerals, fossils, and land formations.

GEOMORPHOLOGY: The study of landforms and of the forces and processes that have shaped them.

GEOPHYSICS: A branch of the earth sciences that combines aspects of geology and physics. Geophysics addresses the planet's physical processes as well as its magnetic and electric properties and the means by which energy is transmitted through its interior.

GEOSPHERE: The upper part of Earth's continental crust or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

HISTORICAL GEOLOGY: The study of Earth's physical history. Historical geology is one of two principal branches of geology, the other being physical geology.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

HYPOTHESIS: An unproven statement regarding an observed phenomenon.

LAW: A scientific principle that is shown to always be the case and for which no exceptions are deemed possible.

MINERALOGY: The study of minerals (crystalline structures that make up rocks), which includes several smaller subdisciplines, such as crystallography.

PALEONTOLOGY: The study of fossilized plants and animals, or flora and fauna.

PHYSICAL GEOLOGY: The study of the material components of Earth and of the forces that have shaped the planet. Physical geology is one of two principal branches of geology, the other being historical geology.

PHYSICAL SCIENCES: Astronomy, physics, chemistry, and the earth sciences.

PLANETARY SCIENCE: The branch of the earth sciences, sometimes called planetology or planetary studies, that focuses on the study of other planetary bodies. This discipline, or set of disciplines, is concerned with the geologic, geophysical, and geochemical properties of other

KEY TERMS CONTINUED

planets but also draws on aspects of astronomy, such as cosmology.

SCIENTIFIC METHOD: A set of principles and procedures for systematic study that includes observation; the formation of hypotheses, theories, and laws; and continual testing and reexamination.

SCIENTIFIC REVOLUTION: A period of accelerated scientific discovery that completely reshaped the world. Usually dated from about 1550 to 1700, the Scientific Revolution saw the origination of the scientific method and the introduction of ideas such as the heliocentric (Sun-centered) universe and gravity.

SEDIMENTOLOGY: The study and interpretation of sediments, including sedimentary processes and formations.

STRATIGRAPHY: The study of rock layers, or strata, beneath Earth's surface.

STRUCTURAL GEOLOGY: The study of rock structures, shapes, and positions in Earth's interior.

THEORY: A general statement derived from a hypothesis that has withstood sufficient testing.

known as paleobiogeography, or the study of fossils' geographic distribution. The principle subdisciplines of physical geology are:

- Geomorphology: the study of landforms and of the forces and processes that have shaped them
- Structural geology: the study of rock structures, shapes, and positions in Earth's interior
- Mineralogy: the study of minerals (crystalline structures that make up rocks), which includes several smaller subdisciplines, such as crystallography
- Petrology: the study of rocks, which is divided into several smaller subdisciplines, most notably igneous, metamorphic, and sedimentary petrology
- Economic geology: the study of fuels, metals, and other materials from Earth that are of interest to industry or the economy in general
- Environmental geology: the study of the geologic impact of both natural and human activity on the environment.

It should be noted that there is some overlap between historical and physical geology. For instance, sedimentology often is placed under the heading of physical geology, while some sources include a third category of subdisciplines that overlap both historical and physical geology.

OTHER GEOLOGIC SCIENCES. Geology occupies a central place among the geologic sciences or geosciences, but also important are those disciplines and subdisciplines formed, as Holmes pointed out, at the intersections between geology and astronomy, physics, and chemistry, respectively. (Some sources, on the other hand, consider these disciplines to be a part of geology itself. In the present context, the term geologic sciences is used to encompass not only geology but also these related areas of study.)

Planetary science applies the earth sciences paradigm to other planets. Among its important subdisciplines is astrogeology or planetary geology, or the study of the rock record on the Moon, the planets, and other bodies. Also significant is cosmology, the study of the origin, structure, and evolution of the universe, which often is treated as part of astronomy.

Geophysics, or an application of physics to the study of Earth, occupies a position of prominence within the earth sciences. Among the areas it addresses are the production, expenditure, and transmission of energy within Earth as well as the planet's magnetic, electric, and gravitational properties. Geophysics encompasses such areas as geodesy, the science of measuring Earth's

shape and gravitational field. Seismology, or the study of the waves produced by earthquakes and volcanoes, is another important part of geophysics. (On the other hand, volcanology, or the study of volcanoes themselves, would fall more properly under physical geology.)

Geochemistry, which is concerned with the chemical properties and processes of Earth, covers a wide array of natural phenomena—from radioactive isotopes in the ground to life-forms in the biosphere. Under the heading of geochemistry fall several biogeochemical processes, such as the carbon cycle, whose study brings together aspects of the physical sciences geology and chemistry as well as various life sciences.

OTHER EARTH SCIENCES. The hydrological sciences are concerned with the hydrosphere and its principal component, water. These disciplines include hydrology, the study of the water cycle; glaciology, the study of ice in general and glaciers in particular; and oceanography. Clearly, oceanography overlaps with the life sciences; likewise, hydrogeology (the study of groundwater), as its name implies, overlaps with geology.

The atmospheric sciences, obviously, are devoted to the atmosphere. Most notable among these sciences is meteorology, the study of weather patterns, and climatology, the study of temperature and climate. (Paleoclimatology is an important subdiscipline of historical geology.) The atmospheric sciences also are concerned with phenomena ranging from pollution to the optical effects created by the interaction of the Sun's rays with the atmosphere.

Finally, there are miscellaneous areas of study that either are interdisciplinary or cross boundaries between the earth sciences and the social sciences. In the former category, for instance, would be environmental studies that involve aspects of the biosphere, atmosphere, geosphere, and hydrosphere. Examples of the second category are paleoarchaeology, the study of the earliest humans and humanoid forms, and, of course, geography. Also included in this group are such intriguing areas as urban geology, a branch of environmental geology concerned with human settlements.

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MEASURING AND MAPPING EARTH

CONCEPT

Today a sharp distinction exists between the earth sciences and geography, but this has not always been the case. In ancient times, when scientists lacked the theoretical or technological means to study Earth's interior, the two disciplines were linked much more closely. Even in the centuries since these disciplines parted ways, the earth sciences have continued to benefit from a foundation established in part by early geographers, whose work informed the geophysical subdiscipline of geodesy. Like geographers, earth scientists are interested in measuring and mapping Earth, though their interests are quite different. Among the areas of concern to earth scientists are the location of underground resources and the obtaining of data on the planet's gravitational and magnetic fields. In these and other pursuits, earth scientists use a number of techniques and technologies, ranging from the ancient discipline of surveying to the most modern forms of satellite-based remote sensing.

HOW IT WORKS

Geography and Geology

Whereas geology is the study of the solid earth, including its history, structure, and composition, geography is the study of Earth's surface. Geologists are concerned with the grand sweep of the planet's history over more than four billion years, whereas the work of geographers addresses the here and now—or at most, in the case of historical geography, a span of just a few thousand years.

Today the distinctions between these two disciplines are sharp, so much so that most books on the earth sciences barely even mention geography. In a modern university, chances are that the geography and geology/earth sciences departments will not even be located in the same building. Geography, after all, usually is classified among social sciences such as anthropology or archaeology, whereas geology is a "hard science," along with physics or biology.

It is true that the divisions between geography and geology are clear, symbolized by the features that appear or do not appear on the maps used by either discipline. Geography is somewhat concerned with natural features, but its interests include man-made boundaries, points, and such formations as population centers, roads, and so on. Certainly, an atlas may include physical maps, which are dominated by natural features and contain little or no evidence of man-made demarcations or points of interest. Nonetheless, the purpose of a geographical atlas is to identify locations of interest to humans, among them, cities, roads from one place to another, and borders that must be crossed.

By contrast, geologic maps contain detailed information about rock formations and other natural features, with virtually nothing to indicate the presence of humans except as it relates to natural features under study. An exception might be a map designed to be used by paleoarchaeologists, who study the earliest humans and humanoid forms. Their discipline, which combines aspects of the earth sciences and archaeology, is concerned with human settlements, but mostly only prehistoric human settlements.

Despite the depth and breadth of distinctions between them, it is significant that studies in both geography and geology make use of maps. Mapmaking, or cartography, is considered a subdiscipline of geography, yet it is actually an interdisciplinary pursuit (much like many of the earth sciences—see Studying Earth) and combines aspects of science, mathematics, technology, and even art. Although their interests are in most cases quite different from those of geographers, geologists rely heavily on the work of cartographers.

Early Geographic Studies

The history of the sciences has been characterized by the continual specialization and separation of disciplines. Thus, it should not be surprising to discover that to the ancients, the lines were blurred between geography, mathematics, astronomy, and what people today would call earth sciences. Most of the early advances in the study of Earth involved all of those disciplines, an example being the remarkable estimate of Earth's size made by Eratosthenes of Cyrene (*ca.* 276–*ca.* 194 B.C.).

A mathematician and librarian at Alexandria, Egypt, Eratosthenes discovered that at Syene, several hundred miles south along the Nile near what is now Aswan, the Sun shone directly into a deep well and upright pillars cast no shadow at noon on the summer solstice (June 21). By using the difference in angles between the Sun's rays in both locations as well as the distance between the two towns, he calculated Earth's circumference at about 24,662 mi. (39,459 km). This figure is amazingly close to the one used today: 24,901.55 mi. (39,842.48 km) at the equator. Eratosthenes published his results in a book whose Greek name, *Geographica* (Geography), means "writing about Earth." This was the first known use of the term.

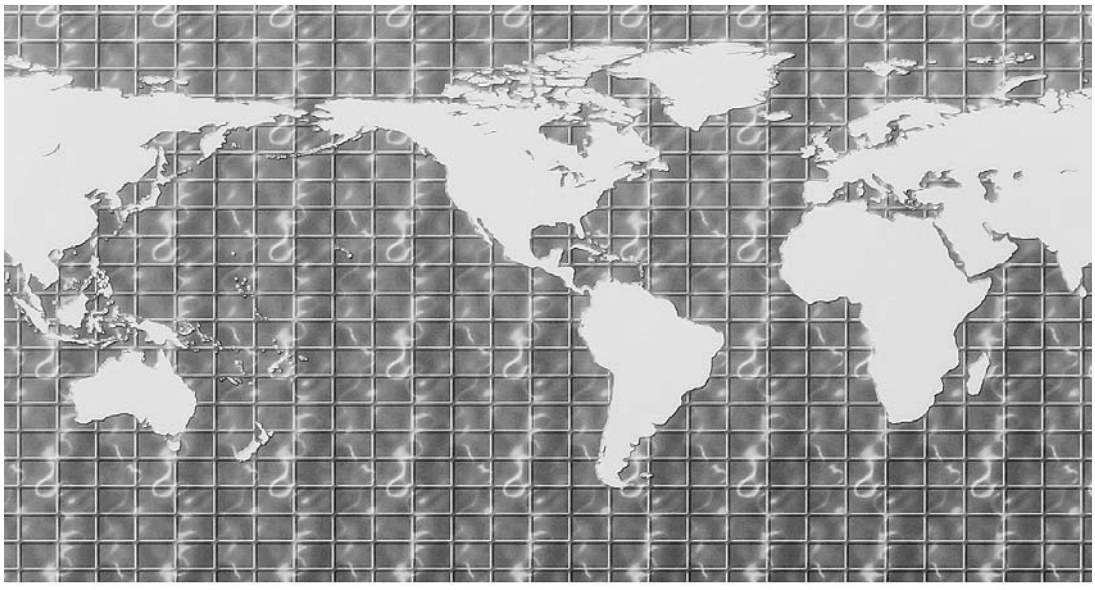
Ptolemy's Geography. Unfortunately, the Alexandrian astronomer Ptolemy (*ca.* A.D. 100–170), one of the most influential figures of the ancient scientific world, rejected Eratosthenes' calculations and performed his own, based on faulty information. The result was a wildly inaccurate estimate of 16,000 mi. (25,600 km). More than thirteen centuries later, Christopher Columbus (1451–1506) relied on Ptolemy's figures rather than those of Eratosthenes, whose work was probably unknown to him. Thinking that the circumference of Earth was two-thirds what it actually is, Columbus set sail westward from Spain—something he might not have done if he had known about the "extra" 8,000 mi. (12,874 km) that lay to the west of Europe.

Nonetheless, in his *Hyphegesis geographike* (Guide to geography), Ptolemy did make useful contributions to geographical study. He helped popularize the use of latitude and longitude lines, first conceived by the Greek astronomer and mathematician Hipparchus (*fl.* 146–127 B.C.), and rejected the widespread belief that a vast ocean, known to the ancients as "the Ocean Sea," surrounded the entire world. He also presented a set of workable mathematical principles for representing the spherical surface of Earth on a flat page, always a problem for cartographers.

In addition, Ptolemy established the practice of orienting maps with north at the top of the page. Today this is taken for granted, but in his time cartographers depicted the direction of the rising Sun, east, at the top of their maps. Ptolemy used a northward orientation because the Mediterranean region that he knew extended twice as far east to west as it did north to south. To represent the area on a scroll, the form in which books appeared during his time, it was easier to make maps with north at the top.

Other Ancient Geographers. Most other ancient geographers of note were primarily historians rather than scientists, preeminent examples being the Greek Herodotus (*ca.* 484–*ca.* 430–420 B.C.), the father of history, and Strabo (*ca.* 64 B.C.–*ca.* A.D. 24), whose work provides some of the earliest Western descriptions of India and Arabia. An exception was Pomponius Mela (*fl. ca.* A.D. 44), whose work would fit into the subdiscipline known today as physical geography, concerned with the exterior physical features and changes of Earth.

In his three-volume *De situ orbis,* (A description of the world), Mela introduced a system of five temperature zones: northern frigid, northern temperate, torrid (very hot), southern temperate, and southern frigid. Unlike many scientific works of antiquity, Mela's geography has remained influential well into modern times, and his idea of the five temperature zones remains in use. Mela and Ptolemy, who followed him by about a century, were among the last geographers



Mercator cylindrical projection of the continents of Earth, showing the characteristic exaggeration in scale of land masses near the poles. *(© R. Winter/Photo Researchers. Reproduced by permission.)*

of note in the West for more than a thousand years.

THE SEPARATION OF GEOGRAPHY AND EARTH SCIENCES. During the first half of the Middle Ages significant work in cartography took place in the Muslim world and in the Far East, but not in Europe. Only in the course of the Crusades (1095–1291) did Europeans become interested in exploration again, and this interest grew as the Mongol invasions of the thirteenth century opened trade routes from Europe to China for the first time in a thousand years. The crusading and exploring spirits met in Henry the Navigator (1394–1460), the prince who, while he never actually took part in any voyages himself, quite literally launched the Age of Exploration from his navigation school at Sagres, Portugal.

In the two centuries that followed, European mariners and conquerors explored and mapped the continents of the world. Along the way, these nonscientists sometimes added knowledge to what would now be considered the earth sciences, as when the Italian explorer Christopher Columbus (1451–1506) became the first to notice magnetic declination. (See Geomagnetism for more on this subject.) Meanwhile, Columbus's contemporary, the Italian artist and scientist Leonardo da Vinci (1452–1519), as well as Georgius Agricola (1494–1555) of Germany, known as the father of mineralogy, conducted some of the first modern studies in the earth sciences. (See Studying Earth for more about Leonardo's and Agricola's contributions.)

In the sixteenth century, the Flemish cartographer Gerhardus Mercator (1512–1594) greatly advanced the science of mapmaking with his development of the Mercator projection. The latter method, still used in many maps today, provided an effective means of rendering the spherical surface of Earth on a two-dimensional map. By that time, cartography had emerged as a vital subdiscipline, and over the ensuing two centuries the separation between geography and the earth sciences became more and more distinct.

The full separation of disciplines took place in the eighteenth century, when the German geographer Anton Friedrich Büsching (1724–1793) pioneered modern scientific geography. Beginning in 1754, Büsching published the 11-volume *Neue Erdbeschreibung* (New description of the earth), which established a foundation for the study of geography in statistics rather than descriptive writing. During the same century geology was in the middle of its own paradigm shift. Until the time of the Scottish geologist James Hutton (1726–1797), a near exact contemporary of Büsching, geologists had been concerned primarily with explaining how the world began—a topic that almost inevitably led to conflict over religious questions (see Earth, Science, and Nonscience). Hutton, known as the father of

geology, was the first to transcend this issue and instead offer a theory about the workings of Earth's internal mechanisms.

Surveying

The era of Büsching and Hutton coincided with that of the English astronomer Charles Mason (1730–1787) and the English surveyor Jeremiah Dixon (*d.* 1777), who in 1763 began their famous survey of the boundary between Pennsylvania and Maryland. It took them five years to survey the 233-mi. (373-km) Mason–Dixon Line, which eventually became known as the border between the free and slave states before the Civil War. Surveying, a profession practiced by such great Americans as the first president, George Washington (1732–1799), and the mathematician and astronomer Benjamin Banneker (1731–1806), eventually became associated with the United States, but it originated in Egypt as early as 2700 B.C.

Surveying is a realm of applied mathematics devoted to measuring and mapping areas of land. Though it is obviously of value to the earth sciences and geography, it has a great deal of importance economically and politically as well. For this reason, the Romans, who were not nearly as inclined toward theoretical study as the Greeks, became preeminent surveyors whose land parcels still can be seen from the air over parts of western Europe. Owing to its great practical importance, surveying—unlike virtually all other forms of learning—continued to thrive in Europe during the early Middle Ages. Nonetheless, surveying improved in the Renaissance and thereafter, as the result of the introduction of new tools and mathematical techniques.

Among these tools were the theodolite, used for measuring horizontal and vertical angles, and the transit, a type of theodolite that employs a hanging plumb bob to determine a level sight line. Mathematical techniques included triangulation, whereby the third side of a triangle can be determined from measurements of the other two sides and angles. The German mathematician Karl Friedrich Gauss (1777–1855), regarded as the father of geodesy, introduced the heliotrope, a mechanism that aids in triangulation. Other tools included the compass, level, and measuring tapes; modern surveying benefits from remote sensing. (Both remote sensing and geodesy are discussed later in this essay.)

REAL-LIFE APPLICATIONS

Geologic Maps and Surveys

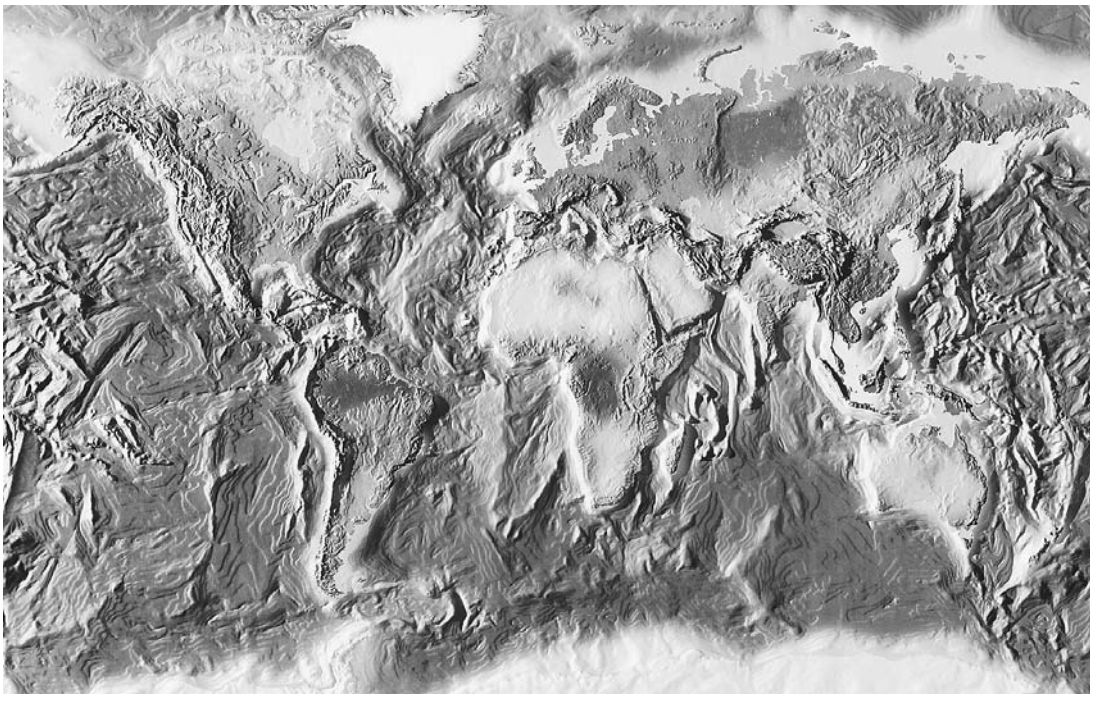
A geologic map shows the rocks beneath Earth's surface, including their distribution according to type as well as their ages, relationships, and structural features. The first geologic map, made in 1743, depicted subterranean East Kent, England. Its creator, the English physician and geologist Christopher Packe (1686–1749), introduced the technique of hachuring, that is, representing relief (elevation) on a map by shading in short lines in the direction of the slopes.

Three years later, the French geologist Jean-Etienne Guettard (1715–1786) made the first geologic map that crossed national lines, thus illustrating the distinction between geology and geography. As Guettard discovered, the geologic features of the French and English coasts along the English Channel are identical, indicating that the areas are connected. At a time when France and England were still bitter political and military rivals, Guettard's work showed that they literally shared some of the same land.

Geologic mapmaking received a further boost in 1815, when the English geologist William Smith (1769–1839) produced what has been called the first geologic map based on scientific principles. Entitled *A Delineation of the Strata of England and Wales with Part of Scotland,* the map used different colors to indicate layers of sedimentation. Roughly 6 ft. by 9 ft. (1.8 × 2.7 m), the map linked paleontology with stratigraphy (the study of fossils and the study of rock layers, respectively) and proved to be a milestone in geologic cartography.

MODERN GEOLOGIC MAPMAKING. Geologic mapmaking changed considerably in the period after World War II. Before that time, geologists did most of their work with the use of topographical maps, or maps that showed only surface features. Following the war, however, aerial photography became much more common, giving rise to the technique of photogeology, the use of aerial photographic data to make determinations regarding the geologic characteristics of an area.

Petroleum companies, which often have taken the lead in developing advanced methods of geologic study, introduced the practice of creating three-dimensional images from the air.



Relief-shaded map of Earth, showing the continents in raised elevation. *(© M. Agliolo/Photo Researchers. Reproduced by permission.)*

They did this by taking pairs of photographs which, when viewed through a stereoscope, provided images that could be studied in great detail for information about all manner of geologic features. Height proved a great advantage, revealing features that would not have been as clear to a geologist working on the ground.

Of course, a great deal of work on the ground was still necessary for confirming the data revealed by aerial surveillance and for other purposes, such as measurement and sample collection. Nonetheless, aerial photography provided an enormous boost to geologic studies, as did the use of satellite imaging from the 1970s onward. Also helpful were such new devices as the handheld magnetometer, which made it relatively easy to separate rocks containing magnetite from other, nonmagnetic samples.

WHY MAKE GEOLOGIC MAPS? One might wonder why any of this is important, aside from a purely academic interest in the structure of rocks under the ground. In fact, the need for precise geologic data goes far beyond "purely academic interests," as the reference to oil companies suggests. Geologic mapmaking is critical to the location of oil as well as minerals and other valuable natural resources—including the most useful one of all, water.

Likewise it is necessary to have accurate geologic information before undertaking a large engineering project, such as the building of a road or bridge. In such situations, geologic studies can quite literally be a matter of life and death, and eventually such studies may save more lives by aiding in the prediction of earthquakes or volcanoes. Geologic data is also a critical part of studies directed toward environmental protection, both for areas designed to remain natural habitats and for those designated for development. And, finally, there are studies whose purpose is purely, or mostly, academic but that reveal a great deal of useful information about the history of the planet, the forces that shaped it, and perhaps even future events.

GEOLOGIC SURVEYS. Geologic mapmaking is so vital, in fact, that national governments have undertaken large-scale and ongoing geologic studies since 1835. That was the year that Great Britain became the first country to establish a geologic survey, with the aim of preparing a geologic map of the entire British Isles. The project began with the mapping of Cornwall and southern Wales and has continued ever since, with the addition of new details as they have become available.

In the ensuing years several other countries established their own geologic surveys, including the United States in 1889. (The Web site of the U.S. Geological Survey is listed in the bibliography.) Other important national geologic surveys include those of France, Canada, China, and Russia. The last of these surveys is of particular interest, dating as it does from the "Stone Department," a mineralogical survey established in 1584. Today even much smaller nations, such as Uruguay, Slovakia, and Namibia, have their own national geologic surveys.

Over the years, techniques of information gathering have evolved, particularly with the development of satellite remote-sensing technology. So, too, have the areas under the purview of various national geologic surveys, which since the 1950s have undertaken the mapping of the continental shelves adjacent to their own shorelines. (In addition, the nations claiming territories in Antarctica, including Britain and the United States, have mapped the geologic features of that continent extensively, though mining or other economic development there is forbidden.) The U.S. Geological Survey has also seen its scope extended to include studies on such issues as radioactive waste disposal and prediction of natural hazards, among them, earthquakes in urban areas.

Geophysical Measurements

Geophysics is a branch of the earth sciences that combines aspects of geology and physics. Among the areas it addresses are Earth's physical processes as well as its gravitational, magnetic, and electric properties and the means by which energy is transmitted through its interior. Areas of geophysics with a particular focus on measurement and mapping include the study of geomagnetism, or Earth's magnetic field, and geodesy, which is devoted to the measurement of Earth's shape and gravitational field.

The measurement of gravitational fields involves the use of either weights dropped in a vacuum or mechanical force-balance instruments. The first of these techniques is much older than the other and provides an absolute measure of the gravitational field in a given area. As for force-balance instruments, they are similar in principle to scales and furnish a relative measure of the gravitational field. To compare the gravitational field at different positions, however, it is necessary to establish a frame of reference. This is known as the *geoid,* a surface of uniform gravitational potential covering the entire earth at a height equal to sea level. (See Gravity and Geodesy for more on these topics.)

Geodetic measurements of earth's surface. As noted, geodesy is concerned not only with Earth's gravitational field but also with its shape, and earth scientists working on this aspect of the subdiscipline employ many of the techniques and equipment described earlier with regard to geography and surveying. Eratosthenes's measurement of Earth's size is thought to be the first geodetic measurement, and in performing geodetic measurements today, earth scientists often employ concepts familiar to surveyors.

Among these concepts is triangulation, which was developed in the sixteenth century by the Dutch mathematician Gemma Frisius (1508–1555). Triangulation remained an important method of geodetic measurement until the development of satellite geodesy made possible simpler and more accurate measurements through remote sensing. Even today triangulation is still used by geologists without access to satellite data. In performing measurements using triangulation, geologists employ the theodolite, and typically at least one triangulation point is highly visible—for instance, the top of a mountain.

Until the 1950s scientists used a measuring tape of a material called Invar, a nickel-iron alloy noted for its tendency not to expand or contract with changes in temperature. From that time, however, electronic distance measurement (EDM) systems, which employ microwaves or visible light, came into use. EDM helped overcome some of the possibilities for error inherent in using any kind of tape, for example, the likelihood that it would sag and thus render incorrect measurements. Furthermore, EDM tended to reduce errors caused by atmospheric refraction.

With the advent of the United States program in the 1960s, increasingly more sophisticated forms of geodesic remote-sensing technology came into use. Among these techniques is satellite laser ranging, which relies on measurements of the amount of time required for a laser pulse to travel from a ground station to a satellite and back. Before the development of the global posi-

KEY TERMS

CARTOGRAPHY: The creation, production, and study of maps. Cartography is a subdiscipline of geography and involves not only science but also mathematics, technology, and even art.

DOPPLER EFFECT: The change in the observed frequency of a wave when the source of the wave is moving with respect to the observer.

FIELD: A region of space in which it is possible to define the physical properties of each point in the region at any given moment in time.

GEODESY: An area of geophysics devoted to the measurement of Earth's shape and gravitational field.

GEOGRAPHY: A social science concerned with the description of physical, biological, and cultural aspects of Earth's surface and with the distribution and interaction of these features. Compare with geology.

GEOID: A surface of uniform gravitational potential covering the entire earth at a height equal to sea level.

GEOLOGIC MAP: A map showing the rocks beneath Earth's surface, including their distribution according to type as well as their ages, relationships, and structural features.

GEOLOGY: The study of the solid earth, in particular, its rocks, minerals, fossils, and land formations.

GEOPHYSICS: A branch of the earth sciences that combines aspects of geology and physics. Geophysics addresses the planet's physical processes as well as its gravitational, magnetic, and electric properties and the means by which energy is transmitted through its interior.

GEOMAGNETISM: A term referring to the magnetic properties of Earth as a whole, rather than those possessed by a single object or place on Earth.

tioning system (GPS), discussed later, the use of satellite systems necessitated tracking through the Doppler effect, or the change in the observed frequency of a wave when the source of the wave is moving with respect to the observer. Thanks to GPS, put into operation by the U.S. Department of Defense, satellite tracking is much simpler and more accurate today.

GEOMAGNETIC MEASUREMENTS. Ever since the ancient Chinese discovered that pieces of lodestone (magnetite) tend to point north, mariners have used the compass for navigation. The compass was augmented by other navigational devices until it was supplanted by the gyroscope in modern times and still later by more sophisticated devices and methods, such as GPS. Yet a compass still works fine for many a hiker, and its use serves to emphasize the importance of Earth's magnetic field.

Earth has an overall geomagnetic field, and specific areas on the planet have their own local magnetic fields. Thanks in large part to the contributions of Gauss, who developed a standardized local magnetic coordinate system in the early nineteenth century, it became possible to perform reasonably accurate measurements of local magnetic data while correcting for the influence of Earth's geomagnetic field. Indeed, one of the challenges in measuring magnetic fields is the fact that the Earth system possesses magnetic force from so many sources: the molten core, from whence originates the preponderance of Earth's magnetic field; external fields, such as the magnetosphere and ionosphere; local materials, such as magnetite, hematite, or pyrrhotite;

KEY TERMS CONTINUED

HACHURING: A method of representing relief (elevation) on a map by shading in short lines in the direction of the slopes.

MAGNETOSPHERE: An area surrounding Earth, reaching far beyond the atmosphere, in which ionized particles (i.e., ones that have lost or gained electrons so as to acquire a net electric charge) are affected by Earth's magnetic field.

PALEOMAGNETISM: An area of historical geology devoted to studying the direction and intensity of magnetic fields in the past, as discerned from the residual magnetization of rocks.

PALEONTOLOGY: The study of fossilized plants and animals, or flora and fauna.

PHOTOGEOLOGY: The use of aerial photographic data to make determinations regarding the geologic characteristics of an area.

PHYSICAL GEOGRAPHY: A subdiscipline of geography concerned with the exterior physical features and changes of Earth.

POTENTIAL: Position in a field, such as a gravitational force field.

REFRACTION: The bending of light as it passes at an angle from one transparent material into a second transparent material.

REMOTE SENSING: The gathering of data without actual contact with the materials or objects being studied.

STRATIGRAPHY: The study of rock layers, or strata, beneath Earth's surface.

SURVEYING: An area of applied mathematics devoted to measuring and mapping areas of land.

TRIANGULATION: A technique in surveying whereby the third side of a triangle can be determined from measurements of the other two sides and angles.

and even man-made sources of magnetic or electric force.

After making calculations that correct for interfering sources of magnetism, geophysicists study the remaining magnetic anomalies, which can impart extremely valuable information. Classic examples include the discovery that Earth's magnetic polarity has reversed many times, a finding that led to the development of the geophysical subdiscipline known as paleomagnetism. Paleomagnetic studies, in turn, served as a highly significant confirmation of plate tectonics, which originated in the middle of the twentieth century and remains the dominant theory regarding geologic processes. (See Plate Tectonics. For more about geomagnetism, including some of the topics mentioned here, see Geomagnetism.)

Knowing One's Location

In these and other types of studies that involve mapping and measurement, it is important for scientists conducting surveys to be aware of the frame of reference from which they are operating—that is, the perspective from which they view data. Simply put, one must know first where one is before one can measure and map geophysical or other data for surrounding areas. This requires knowledge of latitude and longitude, or east–west and north–south positions, respectively.

From earliest times, mariners and scientists have been able to ascertain latitude with relative ease, simply by observing the angle of the Sun and other stars. Determination of longitude, however, proved much more difficult, because it required highly accurate timepieces. Only in the late eighteenth century, with the breakthroughs

achieved by the British horologist John Harrison (1693–1776) did such calculations become possible. As a result, many a ship's crew was saved from the misfortunes that could result from inaccurate estimates of location.

GLOBAL POSITIONING SYSTEM. By the latter part of the twentieth century, navigational technology had become vastly more sophisticated than it was in Harrison's day. From the 1957 launch of the Soviet satellite *Sputnik 1,* the skies over Earth became increasingly populated with satellites, such that within half a century dozens of countries had payloads in space. Aside from governments and scientific research establishments, even cable television companies used satellites to beam programming to homes all over the industrialized world, a fact that in itself says much about the spread of satellite technology.

Among the most impressive uses of satellites is the GPS, developed by the U.S. Department of Defense to assist in surveillance. GPS consists of 24 satellites orbiting at an altitude of 12,500 mi. (20,000 km). They move in orbital paths such that an earthbound receiver can obtain signals from four or more satellites at any given moment. On board are atomic clocks, which provide exact time data with each signal and eliminate the necessity of the receiver's having such an accurate clock. By receiving data from these satellites, persons on the ground can compute their own positions in terms of latitude and longitude as well as altitude. Not all receivers have access to the most accurate data possible: in line with the strategic mission for which it initiated GPS in the first place, the Defense Department ensures that only authorized personnel receive the most precise information.

Thus, GPS has built-in errors so that civilian users can calculate locations with an accuracy of "only" 328-492 ft. (100–150 m). This, of course, is amazingly accurate, but not as accurate as the data available to those authorized to receive normally encrypted information on the P (Precise) code. The latter provides an accuracy of 3.28-16.4 ft. (1–5 m) instantaneously, and more detailed measurements based on GPS data can be used to achieve accuracy of up to 0.2 in. (5 mm).

Remote Sensing

Many of the methods used by geologists and geophysicists to map and measure Earth make use of remote sensing, the gathering of data without actual contact with the materials or objects being studied. Without remote sensing, it would be impossible to discuss many physical phenomena intelligently, because it is unlikely that any technology ever will make it possible to explore many areas underneath the planet's surface directly.

An example of remote sensing is photogeology, described briefly earlier; so, too, is satellite imaging for data collection. The earth scientist of the twenty-first century likewise has other highly sophisticated forms of technology, such as radar systems or infrared imaging, at his or her disposal. As with many other aspects of geologic mapping and measurement, this one has value far beyond the classroom: remote-sensing studies make it possible, for instance, to observe the environmental impact of deforestation in large geographical areas. (For much more about this subject, see Remote Sensing.)

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REMOTE SENSING

CONCEPT

Scientists of many disciplines are accustomed to studying data that cannot be observed through direct contact. Physicists and chemists, for instance, know a great deal about the structure of the atom, even though even the most high-powered microscope cannot make an atom visible to the human eye. The objects of study for earth scientists are often similarly remote, though not necessarily because they are small. In some cases, the problem is quite the opposite: an area selected for study is too large to provide understanding to geologists working only on the ground. Other areas are simply inaccessible to human beings or even their equipment. This has necessitated the development of remote sensing equipment and techniques, primarily involving views from the air or from space and utilizing electromagnetic radiation across a wide spectrum.

HOW IT WORKS

An Introduction to Remote Sensing

The work of geologists would be much easier if Earth were transparent and they could simply look down into the ground as they would into the sky. But the ground is not transparent; nor, for that matter, is the sky, to which meteorologists look for information regarding atmospheric and weather patterns. Some places are hard to see, and many are difficult or even impossible to visit physically. Some places, such as the Sun or the Earth's core, could not be approached physically even by unmanned technology.

Hence the need for remote sensing, or the gathering of data without actual contact with the materials or objects being studied. Some earth scientists define the term more narrowly, restricting "remote sensing" to the use of techniques involving radiation on the electromagnetic spectrum. The latter category includes visible, infrared, and ultraviolet light as well as lower-frequency signals in the microwave range of the spectrum. This definition excludes the study of force fields involving gravitational or electromagnetic force. In general, in this essay we abide by that more narrow definition, primarily because most forms of remote sensing in use today involve electromagnetic radiation.

Remote sensing is used for a variety of measuring and mapping applications. The reader therefore is encouraged to consult the essay Measuring and Mapping Earth for more on this subject. Applications of remote sensing go far beyond cartography (mapmaking) and measurement, however. As suggested already, remote sensing makes it possible for earth scientists to collect data from places they could not possibly go. In addition, it allows for data collection in places where a human being would be "unable to see the forest for the trees"—which in places such as the Amazon valley is quite literally the case.

The Military Influence

Scientists' understanding of the electromagnetic spectrum was still in its infancy in 1849, when the French army engineer Aimé Laussedat (1819–1907) introduced what was then called iconometry, from the Greek words *icon* ("image") and *-metry* ("measurement"). Laussedat, who experimented with aerial photography



A hand-held global positioning device. *(© Ken M. Johns/Photo Researchers. Reproduced by permission.)*

by means of cameras mounted on balloons or kites, is regarded as a pioneer of photogrammetry, the use of aerial or satellite photography to provide measurements of or between objects on the ground.

A few years later, the United States armies of the Civil War adopted the use of aerial photography for surveillance purposes, mounting cameras on balloons to provide intelligence regarding federal or Confederate positions and troop strength. This fact, combined with Laussedat's status as an army engineer, hints at one of the underlying themes in the history of remote sensing, and indeed of many another technological advance: the influence of the military. It is a fact of human existence that nations from at least the time of the Assyrians, if not the Egyptians of the New Kingdom, have devoted far more attention and resources to military applications than they have to peacetime activities.

On the other hand, societies have benefited enormously from technological and organizational innovations with military origins, innovations whose application later spread to a variety of peacetime uses. Some examples include the adoption of the chariot by the Egyptian army after the Hyksos invasion (*ca.* 1670 B.C.); the Assyrian introduction of logistics in an effort to supply imperial troops (*ca.* 800 B.C.); the Persian development of the postal service (*ca.* 600 B.C.); numerous Roman innovations, particularly in road building (*ca.* 200 B.C.–*ca.* A.D. 200); and the Chinese invention of the wheelbarrow (*ca.* 100 B.C.). And so the list goes, right up to such latter-day American developments as the Internet and GPS, or global positioning system.

MILITARY CONTRIBUTIONS TO REMOTE SENSING. Forms of technology pioneered by military forces and now used in remote sensing include infrared photography, thermal imagery, radar scanning, and satellites. The first of these types of technology makes use of light in the infrared portion of the electromagnetic spectrum—a region that, as its name suggests, is adjacent to the red portion of visible light. Red has the longest wavelength and the lowest frequency of all colors, and infrared has an even longer wavelength and lower frequency. Military forces use infrared photography to distinguish between vegetation and camouflage designed to look like vegetation: live plants reflect infrared radiation, whereas dead ones and camouflaged material absorb it.

Whereas infrared photography measures reflection of infrared radiation, thermal imaging indicates the amount of such radiation that is emitted by the source. Its military origins lie in its use for reconnaissance during night bombing missions. Similarly, radar scanning makes it possible to view targets on the ground, regardless of lighting or cloud cover. Finally, there are satellites, which have extensive surveillance applications. Among the most important examples of military activity above Earth's atmosphere are the 24 satellites of GPS, which make allow U.S. forces to plot positions with amazing accuracy. Less accurate GPS intelligence is also available to civilians. (See Measuring and Mapping Earth for more on GPS.)

REAL-LIFE APPLICATIONS

Photogeology

All of these innovations introduced by the military, of course, have found application for civilian purposes. Thanks in part to improvements in

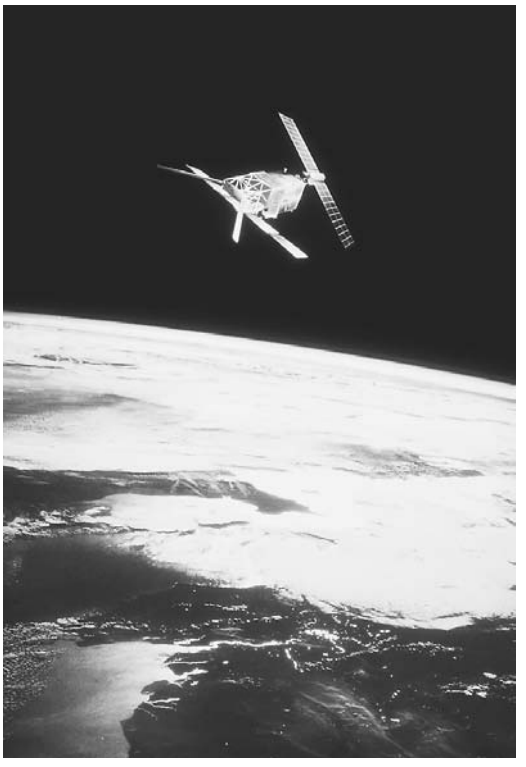
aircraft during World War II, for instance, photogeologic data gathering has increased dramatically in the years since then. Efforts at gaining information by means of airborne sensing devices underwent enormous improvements throughout the middle and latter part of the twentieth century, with the development of technology that made it possible for earth scientists to gather information using techniques beyond ordinary photography, visible light, and airplanes.

Still, much of the remote-sensing activity that takes place today is performed aboard airplanes rather than satellites, using ordinary analogue photography within the visible spectrum. Stereoscopic techniques aid in the visualization of relief, or elevation and other inequalities on a land surface. Humans are used to seeing stereoscopically: the distance between the two eyes on our faces results in a difference between the two images each eye sees. The brain corrects for this difference, rendering a stereoscopic image that is more full and dimensional than anything a single eye could produce. The use of multiple cameras and stereoscopic technology replicates this activity of the human brain and thus provides earth scientists with much more information than they could gain simply by looking at "flat" photographs taken from an airplane.

The materials studied by a geologist, of course, are primarily underground, but Earth's surface furnishes many clues that a trained observer can interpret. Uplands and lowlands tend to suggest different types of rocks, while the direction of a dip in the land can supply volumes of information regarding the stratigraphic characteristics of the region. The presence of vegetation can make it harder to discern such clues, but a careful study of plant life can reveal much regarding minerals in the soil, local water resources, and so on.

Digital Photography

Within both photogeology and the larger realm of remote sensing, several innovations from the 1960s onward have underpinned more effective methods of observation. One of these is digital photography, which is as much of an improvement over old-fashioned photography as compact discs are over phonograph records. In both cases, the contrast is between analog technology and digital technology. In analog photography,



A communications satellite in orbit around Earth. *(© ESA/Photo Researchers. Reproduced by permission.)*

for instance, the image is recorded by a camera and stored on photosensitive materials in a film emulsion. In digital photography the image is recorded on a solid-state device called an image sensor and stored in the camera's memory for transfer to a computer.

An analogue (the preferred spelling for the word as a noun) is just that, a "close copy," whereas digital methods make possible a more exact reproduction of images by assigning to each shade of color a number between 0 and 255. Instead of storing the image in a medium that can be destroyed or lost easily, as is the case with ordinary film, digital images can be saved on a computer, backed up, and sent anywhere in the world via the Internet. Furthermore, these images can be adjusted with the use of a computer, so as to make it easier to see certain features.

Computers and digital photography aid in the creation of false-color imaging, a means of representing invisible electromagnetic data by assigning specific colors to certain wavelengths. An example would be the use of red to depict areas of high energy. This is certainly a false use of color, since red actually has the lowest energy



An aerial photograph shows the Colorado River delta in the Gulf of California. The river itself is the dark hemisphere at the bottom, with its waters branching out through sandbars like the boughs of a tree. *(© Photo Researchers. Reproduced by permission.)*

in the visible spectrum, with purple possessing the highest energy. (The reason we associate red, orange, and yellow with heat and green, blue, and purple with coldness is that in either case, these are the colors objects *reflect,* not the ones they absorb.)

RADAR. Most remote-sensing technology uses light, whether infrared or visible, that falls at the middle to high end of the electromagnetic spectrum. By contrast, at least one important means of remote detection uses microwaves, which are much lower in energy levels. Microwaves carry FM radio and television signals, as well as radar, or *RA*dio *D*etection *A*nd *R*anging.

Radar makes it possible for pilots to "see" through clouds, rain, fog, and all manner of natural phenomena—not least of which is darkness. It also can identify objects, both natural and man-made, on the ground. In addition to its application in remote sensing, radar using the Doppler effect (the change in the observed frequency of a wave when the source of the wave is moving with respect to the observer) helps meteorologists track storms.

In the simplest model of radar operation, a sensing unit sends out microwaves toward the target, and the waves bounce back off the target to the unit. In a monostatic unit—one in which the transmitter and receiver are in the same loca-

tion—the radar unit has to be switched continually between sending and receiving modes. Clearly, a bistatic unit—one in which the transmitter and receiver antennas are at locations remote from one another—is generally preferable, but on an airplane, for instance, there is no choice but to use a monostatic unit.

SATELLITE DATA

The term satellite refers to any object orbiting a larger one; thus, Earth's Moon and all the other moons of the solar system are satellites, as are the many artificial satellites that orbit Earth. In practice, however, most people use the term to refer only to artificial satellites, of which there are many hundreds, launched by entities ranging from national governments to international associations to independent firms. Artificial satellites typically are intended for the purposes of gathering information (i.e., scientific research or military surveillance) or disseminating it (i.e., through satellite television broadcasting).

In launching a satellite, it is necessary to overcome the enormous pull of Earth's gravitational field. This is done by providing the satellite with power through rocket boosters that launch it far above Earth's atmosphere. At a height of 200 mi. (320 km) or more, the satellite is far above the dense gases of the atmosphere yet well within the gravitational field of the planet. The craft is then in a position to orbit Earth indefinitely without the need for additional power from man-made sources; instead, Earth's own gravitational energy keeps the satellite in orbit for as long as the satellite's structure remains intact. (See Gravity and Geodesy for more about the mechanics of orbit.)

The greater the altitude, the longer it takes a satellite to complete a single revolution. One of the most commonly used altitudes is at 22,500 mi. (36,000 km), at which height a satellite takes 24 hours to orbit Earth. Thus, it is said to be in geosynchronous orbit, meaning that it revolves at the same speed as the planet itself and therefore remains effectively stationary over a given area. Some satellites revolve at even higher altitudes—25,000 mi. (40,225 km), which, while it is far beyond the atmosphere, is well within Earth's gravitational field.

LANDSAT. One of the most impressive undertakings in the field of satellite research is Landsat, an Earth-monitoring satellite designed specifically for the use of earth scientists and resource managers. Conceived by the United States Department of the Interior in the mid-1960s, the Landsat project soon came to involve the National Aeronautics and Space Administration (NASA) and the U.S. Geological Survey (USGS; see Measuring and Mapping Earth for more about geologic surveys.) *Landsat 1* went into orbit on July 23, 1972.

Over the years, Landsat has gone into six subsequent generations. *Landsat 6*, launched in 1993, was unable to achieve orbit, but *Landsat 1* lasted more than five times as long as its projected life expectancy of one year. Since 1972 at least one Landsat satellite has been in orbit over Earth, and as of early 2001 both *Landsat 5* (launched in March 1984) and *Landsat 7* (launched in April 1999) were on line. (*Landsat 5* was decommissioned in June 2001.) Over the course of the years, the Landsat governing body has changed. In the 1980s, NOAA (National Oceanic and Atmospheric Administration) took over from NASA, and in October 1985 the Landsat system came under the direction of a commercial organization, the Earth Observation Satellite Company (EOSat).

In contrast to communication satellites, which tend to maintain geosynchronous orbits, Landsat moves at a much lower altitude and therefore orbits Earth much more quickly. *Landsat 7* takes approximately 99 minutes to orbit the planet, thus making 14 circuits in a 24-hour period. Though it never quite passes over the poles, it covers the rest of Earth in swaths 115 mi. (185 km) wide, meaning that eventually it passes over virtually all other spots on the planet.

SATELLITES AT WORK. Landsat and other satellites, such as France's SPOT (Satellite Positioning and Tracking), provide data for governments, businesses, scientific institutions, and even the general public. Following the September 11, 2001, terrorist bombing of the World Trade Center in New York City, for instance, the SPOT U.S. Web site (<http://www.spot.com>) provided viewers with "Images of Infamy": views of downtown Manhattan before and just a few hours after the bombing.

Data from Landsat has been used to study disasters and potential disasters with particular application to the earth sciences. An example is the area of the tropical rainforest in Brazil's Amazon River valley, a region of about 1.9 million sq.

KEY TERMS

CARTOGRAPHY: The creation, production, and study of maps. Cartography is a subdiscipline of geography and involves not only science but also mathematics, technology, and even art.

DOPPLER EFFECT: The change in the observed frequency of a wave when the source of the wave is moving with respect to the observer.

ELECTROMAGNETIC RADIATION: See Electromagnetic spectrum and Radiation.

ELECTROMAGNETIC SPECTRUM: The complete range of electromagnetic waves on a continuous distribution from a very low range of frequencies and energy levels, with a correspondingly long wavelength, to a very high range of frequencies and energy levels, with a correspondingly short wavelength. Included on the electromagnetic spectrum are long-wave and short-wave radio; microwaves; infrared, visible, and ultraviolet light; x rays; and gamma rays.

FALSE-COLOR IMAGING: A means of representing invisible electromagnetic data by assigning specific colors to certain wavelengths.

FREQUENCY: The number of waves, measured in Hertz, passing through a given point during the interval of one second. The higher the frequency, the shorter the wavelength.

GEODESY: An area of geophysics devoted to the measurement of Earth's shape and gravitational field.

HERTZ: A unit for measuring frequency equal to one cycle per second. High frequencies are expressed in terms of kilohertz (kHz; 10^3, or 1,000 cycles per second), megahertz (MHz; 10^6, or one million cycles per second), and gigahertz (GHz; 10^9, or one billion cycles per second).

PHOTOGEOLOGY: The use of aerial photographic data to make determinations regarding the geologic characteristics of an area.

PHOTOGRAMMETRY: The use of aerial or satellite photography to provide measurements of or between objects on the ground.

RADIATION: The transfer of energy by means of electromagnetic waves, which require no physical medium (for example, water or air) for the transfer. Earth receives the Sun's energy, via the electromagnetic spectrum by means of radiation.

RELIEF: Elevation and other inequalities on a land surface.

REMOTE SENSING: The gathering of data without actual contact with the materials or objects being studied.

STRATIGRAPHY: The study of rock layers, or strata, beneath Earth's surface.

WAVELENGTH: The distance between a crest and the adjacent crest or a trough and the adjacent trough of a wave. Wavelength is inversely related to frequency, meaning that the shorter the wavelength, the higher the frequency.

mi. (five million sq km), in which deforestation is claiming between 4,250 sq. mi. and 10,000 sq. mi. (11,000–26,000 sq km) a year. This is an extremely serious issue, because the Amazon basin represents approximately one-third of the total rainforest area on Earth. Earlier estimates, however, had suggested that deforestation was claiming up to three times as much as it actually is, and Landsat provided a more accurate figure.

Because of its acute spatial resolution (98 ft., or 30 m, compared with more than 0.6 mi., or 1 km), Landsat is much more effective for this purpose than other satellite systems operated by NOAA or other organizations. It is also cheaper to obtain images from it than from SPOT. Over the years, Landsat has provided data on urban sprawl in areas as widely separated as Las Vegas, Nevada, and Santiago, Chile. It has offered glimpses of disasters ranging from the eruption of Mount Saint Helens, Washington, in 1980 to some of the most potent recent examples of destruction caused by humans, including the nuclear disaster at Chernobyl, Ukraine, in 1986 and the fires and other effects of the Persian Gulf War of 1990–1991. (For more on this subject, see the Earthshots Web site, operated by USGS.)

Not all the news from Landsat is bad, as a visit to the *Landsat 7* Web site (<http://landsat.gsfc.nasa.gov/>) in late 2001 revealed. Certainly there were areas of concern, among them, flooding in Mozambique and runaway development in Denver, Colorado. But images taken over the Aldabra atoll in the Seychelles showed the world's largest refuge for giant tortoises. And shots taken from Landsat over Lake Nasser in southern Egypt during the latter part of 2000 showed four lakes created by excess water from Nasser. As a result, that region of the Sahara had new lakes for the first time in 6,000 years.

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SCIENCE OF EVERYDAY THINGS

Real-Life Earth Science

PLANETOLOGY

PLANETARY SCIENCE

SUN, MOON, AND EARTH

PLANETARY SCIENCE

CONCEPT

The term *planetary science* encompasses a whole range of studies involving a combination of earth sciences and astronomy. Sometimes known as planetology or planetary studies, these disciplines are concerned primarily with the geologic, geophysical, and geochemical properties of other planets. They also draw on areas of astronomy, such as cosmology, a fascinating discipline devoted to the study of the origin, structure, and evolution of the universe. As always when considering realms beyond our Earth, there are many surprises. Indeed, the more one learns about Earth's relationship to the rest of the cosmos, the harder it is to say which is more intriguing: the many factors that make Earth different or the myriad ways that our home planet is just like the rest of the known universe.

HOW IT WORKS

Earth and the Cosmos

Most of us spend our daily lives without devoting a great deal of thought to what lies beyond Earth. People who live outside cities are perhaps more attuned to the cosmos than are their urban counterparts, simply because they see the vast oceans of stars that cover the sky on a clear night. But a person who lives in the city, where bright lights and smog conspire to cover all but the brightest heavenly bodies, rarely finds a reason to look up into the night sky.

One reason people spend little time thinking about the cosmos is that to do so ultimately fills one with a sense of awe bordering on dread. We know that Earth is but one planet of nine, revolving around an average-sized star, the Sun, somewhere between the center and the edge of a galaxy called the Milky Way—itself just one of many galaxies in the universe. This awareness naturally makes a person feel small and almost inevitably raises questions about the nature of the soul, divinity, and the afterlife.

RELIGION, PHILOSOPHY, MYSTICISM, AND SCIENCE. Such questions are a natural accompaniment to of our feeling that if one person is so truly insignificant in this vast cosmos, there must be something else that gives meaning to the structure of reality. These vast issues, of course, are properly addressed not by science but by theology and philosophy. Science, on the other hand, is concerned simply with the facts of how the universe emerged and how Earth fits into the larger picture.

Yet it is easy to see how ancient peoples would have perceived no distinction between religion and science where the study of the cosmos was concerned. The Babylonians, for instance, had no concept of any difference between scientific astronomy and astrology, which today is recognized as a superstitious and thoroughly unscientific pursuit. The Greeks modeled the cosmos on their philosophical systems, which provided a hierarchy of material forms and an ordered arrangement of causes and substances. And the Judeo-Christian tradition depicts a universe fashioned by a loving, all-powerful creator who designed the human being in his own image.

In the belief systems of Judaism and Christianity, handed down through the Bible, the cosmos is depicted as the setting of a vast spiritual drama centered around the themes of free will,

sin, and redemption. The Bible never says that Earth is the center of the physical universe, but it clearly presents it as the center of the spiritual one. This is understandable enough, especially if human beings truly are the only intelligent lifeforms; unfortunately, these spiritual ideas eventually informed an erroneous cosmology that depicted Earth as the physical center of the cosmos.

Cosmology

In fairness to Christianity, it should be said that most religious, philosophical, and even scientific traditions before about 1500 depicted Earth as the center of the universe. Indeed, it required a great feat of insight to discern that Earth is not the center. The same is true of many other discoveries about the cosmos, where nothing is as it appears when simply gazing into the night sky.

In a scene from his great novel *The Adventures of Huckleberry Finn* (1884), Mark Twain aptly illustrated the impossibility of understanding the universe simply on the basis of unaided intellect. Huck and the runaway slave Jim have just finished supper and are lying on their backs and staring up at the stars, speculating as to their origins. One of them comes up with a theory that seems altogether plausible on the face of it: the Moon, because it looks larger than the stars, must have laid them like eggs. A similar scene occurs in the children's movie *The Lion King* (1994), in which one character postulates that the stars have become stuck to the sky like flies on flypaper. When another character, the warthog Pumbaa, correctly suggests that the stars are actually great balls of burning gas billions of miles away, his companions laugh this off as preposterous.

ARISTARCHUS AND HIPPARCHUS. Although they lacked telescopes, the Greeks developed rather sophisticated (though in many cases wrong) ideas concerning the arrangement of the cosmos. Most notable among these early thinkers was the astronomer Aristarchus of Samos (*ca.* 320–*ca.* 250 B.C.), who proposed that Earth rotates on its axis once every day and revolves with other planets around the Sun. He also correctly suggested that the Sun is larger than Earth.

Unfortunately, the astronomer Hipparchus (146–127 B.C.) rejected this heliocentric, or Sun-centered, cosmology in favor of a geocentric, or Earth-centered, model. Among Hipparchus's later followers was the Alexandrian Ptolemy (*ca.* A.D. 100–170), destined to become the most influential astronomer of ancient and medieval times, who established geocentric cosmology as a guiding principle of astronomy.

THE PTOLEMAIC SYSTEM. The influence of Ptolemy's erroneous ideas is partly an accident of history. He lived, as it turned out, in the last great era of civilization: ten years after his death came that of the Roman emperor Marcus Aurelius (A.D. 121–180), whose passing marked the beginning of Rome's decline over the next three centuries. Learning in western Europe virtually ceased until about 1200, and even though the Muslim world produced several thinkers of note during this period, most of them worked within the tradition established by Ptolemy. Muslim thinkers' respect for Ptolemy is reflected in the name that Arab translators gave to his most important writing: *al-majisti* or "majesty." When this work made its way to Europe, it became known as the *Almagest.*

The Ptolemaic system proves that it is possible to prove anything, if one creates a methodology elaborate enough. Of course, as we know now, Earth is not the center of the universe, but pure observation alone did not reveal this, and Ptolemy's cosmology worked because he developed mathematics and ideas of planetary motion that made it workable. For instance, not only did planets orbit around Earth in Ptolemy's cosmology, but they also moved in circles around the paths of their own orbits. Of course, they do revolve on their axes, but that was not part of Ptolemy's model. In fact, it is hard to find an analogy in the real world, with the exception of some bizarre amusement park ride, for the form of motion Ptolemy was describing.

He was trying to explain retrograde motion, or the fact that other planets seem to speed up and slow down. Retrograde motion makes perfect sense once one understands that Earth is moving even as the other planets are moving, thus creating the optical illusion that the others are changing speeds. Since the Ptolemaic system depicted a still Earth in the middle of a moving universe, however, the explanation of retrograde motion required mental acrobatics.

CHALLENGING PTOLEMY. Although it is incorrect, the Ptolemaic system was a creation of genius; otherwise, it could not have survived for as long as it did. Even with the

recovery of learning in Europe during the late Middle Ages, scientists continued to uphold Ptolemy's ideas. Instead of discarding his system, or at least calling it into question, astronomers simply adjusted the mathematics and refined their ancient forebear's physical model to account for any anomalies.

The revolution against Ptolemy began quietly enough in the fifteenth century, when the Austrian astronomer and mathematician Georg Purbach (1423–1461) noted the inaccuracies of existing astronomical tables and the need for better translations of Greek texts. Purbach attempted to produce a revised and corrected version of the *Almagest,* but he died before completing it. The job fell to his student, Johann Müller, who was known as Regiomontanus (1436–1476).

The *Epitome of the Almagest* (1463), begun by Purbach and completed by Regiomontanus, proved to be a turning point in astronomy. Like their medieval predecessors, the two men started out working in the Ptolemaic tradition, but by showing the errors in Ptolemy's work, they actually were criticizing him. Their discoveries were not lost on a young Polish astronomer named Nicolaus Copernicus (1473–1543).

THE COPERNICAN REVOLUTION. The story of the Copernican Revolution, the opening chapter in a larger movement known as the Scientific Revolution, is among the greatest sagas in the history of thought. It was a watershed event, marking the birth of modern science as such, but the change in thought patterns created by this revolution was not so much the work of Copernicus as it was of the Italian astronomer Galileo Galilei (1564–1642). Although he often is given less attention than Copernicus and the other most noted figure of the Scientific Revolution, the English natural philosopher Isaac Newton (1642–1727), Galileo was a thinker of the first order who took Copernicus's discoveries much further.

Copernicus had been concerned with how the planets move as they do, and in the course of his work he showed that all of them (Earth included) move around the Sun. Galileo, on the other hand, set out to discover *why* the planets revolve around the Sun, and in so doing he discovered the principles of inertia and gravitational acceleration that would influence Newton. He made numerous other contributions, such as the discovery that Jupiter had moons, but by far his greatest gift to science was his introduction of the scientific method.

Thanks to Galileo and others who later refined the method, thinkers would no longer be content to let mere conjecture guide their work. Before his time, scientists generally had followed a pattern of absorbing the received wisdom of the ancients and then seeking evidence that confirmed those suppositions. The new scientific method, on the other hand, required rigorous work: detailed observation, the formation of hypotheses, testing of hypotheses, formation of theories, testing of theories, formation of laws, testing of laws—and always more observation and testing.

REAL-LIFE APPLICATIONS

Gravity, the Sun, and Earth

A fourth key figure in the Scientific Revolution was the German astronomer Johannes Kepler (1571–1630), whose laws of planetary motion directly influenced Newton's laws of gravitation and motion. Thanks to Kepler, we know that planets do not make circular orbits around the Sun; rather, those orbits are elliptical. As Newton later showed, the reason for this is the gravitational pull exerted by the Sun.

Gravitational force explains why Earth, the Sun, and all celestial bodies larger than asteroids are round—but also why they cannot be *perfectly* round. As to the latter issue—the fact that Earth bulges near the equator—it is a consequence of its motion around its axis. Because it is spinning rapidly, the mass of the planet's interior responds to the centripetal (inward) force of its motion, producing a centrifugal, or outward, component. If Earth were standing still, it would be much nearer to the shape of a sphere.

MASS AND SPHERICITY. Now to the larger question: Why is Earth round? The answer is that the gravitational pull of its interior forces a planetary body to assume a more or less uniform shape. Furthermore, the larger the mass of an object, the greater its tendency toward roundness. Earth's surface has a relatively small vertical differential: between the lowest point and the highest point is just 12.28 mi. (19.6 km), which is not a great distance, considering that Earth's radius is about 4,000 mi. (6,400 km).



Johannes Kepler *(The Bettmann Archive. Reproduced by permission.)*

An object of less mass is more likely to retain a shape that is less than spherical. This can be shown by reference to the Martian moons Phobos and Deimos, both of which are oblong, and both of which are tiny, in terms of size and mass, compared with Earth's Moon. Mars itself has a radius half that of Earth, yet its mass is only about 10% of Earth's, and therefore it is capable of retaining a less perfectly spherical shape.

There is also the possibility of more pronounced differences in elevation, and thus it should not be surprising to learn that Mars is also home to the tallest mountain in the solar system. Standing 15 mi. (24 km) high, the volcano Olympus Mons is not only much taller than Earth's tallest peak, Mount Everest (29,028 ft., or 8,848 m), it is also 22% taller than the distance from the top of Mount Everest to the lowest spot on Earth, the Mariana Trench in the Pacific Ocean (–36,198 ft., or –10,911 m).

Why Earth Is Special

With regard to gravitation, a spherical object behaves as though its mass were concentrated near its center. Indeed, 33% of Earth's mass is at is core (as opposed to the crust or mantle), even though the core accounts for only about 20% of the planet's volume. Geologists believe that the composition of Earth's core must be molten iron, which creates the planet's vast electromagnetic field.

Certain particulars of Earth's core lead us to answering another great question about our home planet: Why is it alone capable of sustaining life—as far as we can tell—while the other planets of our solar system are either hellish worlds of fire or frigid, forbidding realms of ice crystals and liquefied gas?

Density of Earth's Interior. At first glance, Earth seems to have few distinctions other than its ability to support life: it is neither the largest nor the smallest planet in the solar system, positions held by Jupiter and Pluto, respectively. (Earth ranks fifth.) Earth has a moon, but that is hardly a distinction: Saturn has 18 moons. And not only does Olympus Mons tower over Everest, but the gaseous oceans of Jupiter also are much deeper than the Mariana Trench. In the lists of planetary superlatives, Earth has only one: it is the most dense.

The only bodies that come close are Mercury and Venus, which along with Earth and Mars are designated as terrestrial planets. (Earth's Moon often is considered along with the terrestrial planets because its composition is similar to them and because it is a relatively large satellite.) The terrestrial planets are small, rocky, and dense; have relatively small amounts of gaseous elements; and are composed primarily of metals and silicates. This is in contrast to the Jovian planets, which are large, low in density, and composed primarily of gases. (The Jovian planets usually are designated as the four giants Jupiter, Saturn, Uranus, and Neptune. Pluto, the smallest of all nine planets, has a density higher than any Jovian planet.)

Density is simply the ratio of mass to volume, meaning that Earth packs more mass into a given volume than any other body in the solar system. Saturn, least dense among the planets, has a mass 95.16 times as great as that of Earth, yet its volume is 764 times greater, meaning that its density is only about 12% of Earth's. But whereas Saturn and other Jovian planets are composed primarily of gases surrounding small, dense cores, Earth—beneath its atmospheric layer and it waters—is a hard little ball. Its core, composed of iron, nickel, and traces of other elements, including uranium, is relatively heavy.

That gives it a strong gravitational pull and, in combination with the comparatively high speed of the planet's rotation, causes Earth to have a powerful magnetic field. It is also important to note the significance of planetary mass in making possible the formation of an atmosphere. Because of their mass, larger planetary bodies exert enough gravitational pull to retain gases around their surfaces; by contrast, the Moon and Mercury are too small and have no atmosphere. Of course, Earth is the only planet whose atmosphere is capable of sustaining life as we know it, and this is a result of activity beneath the planet's surface.

A VOLATILE PLANET. Earth is the only terrestrial planet on which the processes of plate tectonics, or the shifting of plates beneath the planetary surface, take place. The other terrestrial planets have crusts of fairly uniform thickness, suggesting that they have never experienced the internal shifting that has helped give our planet its unique topography. Earth also has a relatively thin lithosphere—the upper layer of the planetary surface, including the crust and the brittle portion at the top of the mantle—which helps make it a particularly volatile body.

Of the terrestrial planets, the only ones still given to volcanic activity are Earth and Venus. Mars seems to have experienced volcanic activity at some point in the past billion years, while Mercury and the Moon have not had volcanoes for several billion years. This is also an important factor in determining Earth's capacity to support living things, because volcanoes—which transport gases from the planet's interior to its atmosphere—have been crucial to the creation of the conditions necessary for sustaining life.

The heat generated by internal volatility is also a component influencing the sustainability of life on Earth. At the time Earth and other planets were formed, some 4.5 billion years ago, the planets experienced such heat that they melted, causing a separation of chemical compounds. The heavier compounds, mostly containing iron, sank to the core of the planet, where they remain today, while the lighter ones rose to the surface. Included in these lighter substances were oxygen and other elements essential to the sustenance of life. Even now Earth and Venus, because of their volcanic activity, are cooling at rates slower than those of the other planets, and this has facilitated the separation of elements.



THE SILHOUETTE OF A STARGAZER AGAINST THE MILKY WAY. *(© F. Zullo/Photo Researchers. Reproduced by permission.)*

THE CREATION AND SUSTENANCE OF LIFE. Aside from the distinctive features of its core, Earth's position relative to the Sun has helped make it possible for life to take root on this planet. For decades scientists believed that Earth is unique in possessing that life-sustaining compound of hydrogen and oxygen, H_2O or water; but now we know that even Jupiter—not to mention Venus and Mars—have water on their surfaces. The problem is that Venus's water is too hot, existing as vapor in the upper atmosphere, while the water on Mars and Jupiter takes the form of ice crystals. Earth is uniquely placed to sustain liquid water.

The existence of liquid water made it possible for the first microorganisms to form on Earth, leading over hundreds of millions of years to the development of the complex biosphere known today. The existence of life in simple forms promoted the development of the atmosphere and geosphere, because these life-forms took in carbon dioxide and water, processed them, and returned them to the environment as oxygen and organic materials.



Computer image of the nine planets of our solar system. *(© Photo Researchers. Reproduced by permission.)*

The Solar System and Beyond

The reader may have noticed that earlier in this essay, we ceased discussing progress in cosmology after about 1650. This is not because nothing happened after that time; on the contrary, the centuries that have elapsed since then have seen the greatest progress in astronomical study since the dawn of civilization. To give this topic the coverage it warrants, however, would require a lengthy discussion—one that would take us away from the earth sciences and toward the sister science of astronomy.

Up until the Scientific Revolution, the earth sciences hardly existed, except inasmuch as various people over the millennia had recorded data concerning Earth and made sometimes unscientific speculations regarding its origin and composition. As the oldest of the physical sciences, astronomy was much more mature, but even it could progress only so far under the restrictions of the Ptolemaic system. Unfettered, it began to progress rapidly, and the result has been an unfolding vision of the universe that is at once more clear and more complex.

THE SIZE OF THE UNIVERSE. One of the dominant themes in astronomy from Galileo's time to the present day is astronomers' quite literally expanding vision of the universe. Up until 1781, when the German-born English astronomer William Herschel (1738–1822) discovered Uranus, scientists had known only of the

KEY TERMS

ATMOSPHERE: In general, an atmosphere is a blanket of gases surrounding a planet. Unless otherwise identified, however, the term refers to the atmosphere of Earth, which consists of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon, which together comprise 0.07%.

BIOSPHERE: A combination of all living things on Earth—plants, mammals, birds, reptiles, amphibians, marine life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed. Typically, after decomposing, a formerly living organism becomes part of the geosphere.

CENTRIFUGAL: A term describing the tendency of objects in uniform circular motion to move outward, away from the center of the circle. Though the term *centrifugal force* often is used, it is inertia, rather than force, that causes the object to move outward.

CENTRIPETAL FORCE: The force that causes an object in uniform circular motion to move inward, toward the center of the circle.

COMPOUND: A substance made up of atoms of more than one element chemically bonded to one another.

COSMOLOGY: The study of the origin, structure, and evolution of the universe.

COSMOS: The universe.

ELECTROMAGNETIC ENERGY: A form of energy with electric and magnetic components that travels in waves and which, depending on the frequency and energy level, can take the form of long-wave and short-wave radio; microwaves; infrared, visible, and ultraviolet light; x rays, and gamma rays.

ELEMENT: A substance made up of only one kind of atom. Unlike compounds, elements cannot be chemically broken into other substances.

GEOCENTRIC: Earth-centered.

GEOCHEMISTRY: A branch of the earth sciences, combining aspects of geology and chemistry, that is concerned with the chemical properties and processes of Earth.

GEOLOGY: The study of the solid earth, in particular, its rocks, minerals, fossils, and land formations.

GEOPHYSICS: A branch of the earth sciences that combines aspects of geology and physics. Geophysics addresses the planet's physical processes as well as its magnetic and electric properties and the means by which energy is transmitted through its interior.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

HELIOCENTRIC: Sun-centered.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

HYPOTHESIS: An unproven statement regarding an observed phenomenon.

KEY TERMS CONTINUED

INERTIA: The tendency of an object in motion to remain in motion and of an object at rest to remain at rest.

JOVIAN PLANETS: The planets between Mars (the last terrestrial planet) and Pluto, all of which are large, low in density, and composed primarily of gases.

LAW: A scientific principle that is shown always to be the case and for which no exceptions are deemed possible.

LITHOSPHERE: The upper layer of Earth's interior, including the crust and the brittle portion at the top of the mantle.

MANTLE: The layer, approximately 1,429 mi. (2,300 km) thick, between Earth's crust and its core.

MASS: A measure of inertia, indicating the resistance of an object to a change in its motion. (By contrast, weight—which people tend to think of as similar to mass—is a measure of gravitational force, or mass multiplied by the acceleration due to gravity.)

PLANETARY SCIENCE: The branch of the earth sciences, sometimes known as planetology or planetary studies, that focuses on the study of other planetary bodies. This discipline, or set of disciplines, is concerned with the geologic, geophysical, and geochemical properties of other planets but also draws on aspects of astronomy, such as cosmology.

PROTON: A positively charged particle in the nucleus of an atom.

SCIENTIFIC METHOD: A set of principles and procedures for systematic study that includes observation; the formation of hypotheses, theories, and laws; and continual testing and reexamination.

SCIENTIFIC REVOLUTION: A period of accelerated scientific discovery that completely reshaped the world. Usually dated from about 1550 to 1700, the Scientific Revolution saw the origination of the scientific method and the introduction of such ideas as the heliocentric (Sun-centered) universe and gravity.

TERRESTRIAL PLANETS: The four inner planets of the solar system: Mercury, Venus, Earth, and Mars. These planets are all small, rocky, and dense; have relatively modest amounts of gaseous elements; and are composed primarily of metals and silicates. Compare with Jovian planets.

THEORY: A general statement derived from a hypothesis that has withstood sufficient testing.

UNIFORM CIRCULAR MOTION: The motion of an object around the center of a circle in such a manner that speed is constant or unchanging.

five other planets visible to the naked eye, all of which had been discovered in prehistoric times. (Neptune was discovered in 1846 and Pluto not until 1930.)

In the seventeenth century, astronomers still regarded what we call the solar system as the entire universe, but Herschel was instrumental in ascertaining that Earth is part of a bright band of stars called the Milky Way. Just as Earth once had been believed to be the center of the "universe," or solar system, astronomers then came to believe it was at the center of the Milky Way. Only since 1920 has it been known that our solar system is, in fact, somewhere between the center and

the edge of the vast galaxy. Even the Milky Way, composed of several hundred billion stars and about 120,000 light-years in diameter, is not the entire universe; it is only one of many hundreds of galaxies or "island universes."

As discussed at the beginning of this essay, such a scale is almost too much for the human mind to comprehend, particularly inasmuch as Earth is the only planet known to sustain intelligent life. As the British science-fiction writer Arthur C. Clarke (1917–) has observed, either there are other intelligent life-forms out there in the universe, or there are not—and either possibility is mind-boggling.

THE BIG BANG AND THE SOLAR SYSTEM. Not only has astronomers' understanding of the universe expanded, along with their idea of its size; it also appears that the universe itself is expanding. Today the most widely accepted model regarding the formation of the universe is the big bang theory, first put forward by the Belgian astrophysicist Georges Édouard Lemaître (1894–1966) in 1927. According to this theory, an explosion 10-20 billion years ago resulted in the rapid creation of all matter in the universe, and that matter is continuing to move outward, expanding the frontiers of the universe.

Our own solar system appears to be about five billion years old, meaning that the Sun is a relatively young star. It seems that the future solar system was just one of many great balls of gas, rotating as they moved outward, that were scattered around the universe as a result of the big bang. Just as these balls of gas exploded from the center, the material of the various stars emerged from the center of the ball that became our solar system.

FORMATION OF THE PLANETS. The proto–solar system we have described here was a great rotating cloud, and though it has long since ceased to be a cloud, it continues to rotate—only now it is in the form of planets turning around a sun at the center. The hottest portion of the cloud, at the center, became the Sun, while cooler portions at the fringes became planets. The Sun itself is composed primarily of hydrogen and helium, the two most plentiful elements in the universe. In the extraordinarily high temperatures on the Sun, atoms of hydrogen (which has one proton in its nucleus) experience nuclear fusion, becoming atoms of helium, which has two protons. It appears that continued fusion resulted in the creation of the heavier elements (for instance, nitrogen, carbon, oxygen, and silicon) of which the planets—in particular, our own—are composed.

Earth's elemental makeup is discussed elsewhere in this book, as is the structure of its interior. So, too, is the Sun's effect on Earth. These matters are not unrelated. In studying the solar system and the planets that make it up, one is confronted again and again with the fact that a planet's destiny is governed by its position relative to the Sun. Ultimately, the planets in our solar system are ruled by the same principle that drives the sale of real estate: location, location, location!

This is true not only of the atmosphere and temperature of planets but also of their relative density. It is no mistake that the terrestrial planets are closer to the Sun: their internal composition is as it is because these bodies became the destination of most of the heavier elements that emanated from it. Many of the lighter elements continued to move outward, where they gathered around rocky centers to become the mostly gaseous Jovian planets.

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SUN, MOON, AND EARTH

CONCEPT

Earth is intimately tied to the star around which it revolves, the Sun, and the satellite that revolves around Earth itself, the Moon. Without the Sun, of course, life on Earth simply could not exist, not just because of the need for light but to an even greater degree because of the energy it supplies. For that matter, Earth itself would not exist: our planet appears to have developed from the same cosmic cloud that formed the Sun, and without the Sun to hold it in place with its gravitational pull, Earth would go spinning off into space. For all its influence on human life, however, the Sun has less impact on the tides than the Moon, which is smaller but much closer. Together, these two bodies literally define time in human experience, which has been marked by the movements of the Sun and Moon from a time before civilization began.

HOW IT WORKS

Formation of the Sun and Planets

Scientists today believe that the universe began between 10 and 20 billion years ago, with an event nicknamed the "big bang," The galaxies continued (and still continue) to move outward from that center, and among them was our Milky Way. Somewhere between the center and the rim of the Milky Way, a rotating cloud of cosmic gas formed about six billion years ago,

The center of the cloud, where the greatest amount of gases gathered, was naturally the densest and most massive portion as well as the hottest. There, hydrogen—the lightest of all elements—experienced extraordinary amounts of compression, owing to the density of the clouded gases around it, and underwent nuclear fusion, or the bonding of atomic nuclei. This hot center became the Sun about five billion years ago, but there remained a vast nebula of gas surrounding it. As the fringes of this nebula began to cool, the gases condensed, forming solids around which particles began to accumulate. These were the future planets.

THE PLANETS AND THE ELEMENTS. Closest to the Sun, the planets and other satellites were formed of elements that could condense at high temperatures: iron, silicon, aluminum, calcium, and magnesium. These elements, along with oxygen-containing compounds, constituted the material foundation around which other particles accumulated to form the terrestrial planets: Mercury, Venus, Earth, and Mars. Further from the Sun, where temperatures were lower, gaseous compounds—including methane, ammonia, and even water—could condense. These compounds became the basis around which the five outer planets (the four Jovian planets and Pluto) formed.

The process of planetary formation involved additional steps and took place over a period of about 500 million years. Some of the factors that played a part in forming Earth are discussed in Planetary Science, but in the present context, let us consider the source of those elements mentioned here. Did they just magically form? Were they always there? In answer to the first question, there is nothing magical about the formation of "new" elements, though it almost seems so. As for the second question, the answer is yes and no.



Earth with the Moon in eclipse. *(© Chris Bjornberg/Photo Researchers. Reproduced by permission.)*

Elements and the Sun

The elements themselves were not always there in the universe or on Earth itself; however, the subatomic building blocks that make them up have indeed existed from the beginning of the universe. The basic atomic structure is as follows. There is a nucleus in which one or more protons (positively charged subatomic particles) may reside along with one or more neutrons, which have no charge. Spinning around the nucleus are one or more electrons, or negatively charged subatomic particles.

The number of protons and electrons in an atom is always the same, meaning that the atom has no electric charge. Atoms that have lost or gained electrons (in which case they would acquire a positive or negative charge, respectively) are called ions. Electrons, which move fast and possess very small mass compared with protons and neutrons, are very easy to dislodge from an atom; on the other hand, it takes an extraordinary event to change the number of protons in the nucleus.

This fact is significant, because it points toward the defining characteristic of an element: the number of protons in the nucleus. Atoms of a particular element *always* have the same number of protons, called their atomic number. The atomic number of an element can be determined by consulting the periodic table of elements: for instance, iron, with an atomic number of 26, *must* have 26 protons in its nucleus. If an atom has 25, it is manganese, and if it is has 27, it is cobalt.

FORMING NEW ELEMENTS. The number of neutrons in the nucleus may vary for atoms within a given element. Atoms that have the same number of protons (and are thus of the same element) but differ in their number of neutrons are called isotopes. Most isotopes are stable, meaning that their chemical composition will remain as it is; however, some isotopes are radioactive, meaning that they experience the spontaneous emission of particles or energy over a given period of time.

Radioactive decay is one of two ways that one element can become another. When a radioactive isotope emits an alpha particle, for example, its nucleus expels a positively charged nucleus consisting of two protons and two neutrons, which is the same thing as a helium atom stripped of its electrons. This obviously changes the number of protons in the nucleus of the isotope and may result in its stabilization. The other means of forming a new element is by nuclear fusion, in which two atomic nuclei fuse or bond.

NUCLEAR FUSION. Note that the first of these means by which elements are formed is subtractive; in other words, with radioactive decay, a different element is formed by the expulsion of protons. Nuclear fusion, on the other hand, is additive, resulting in the creation of different elements by the addition of protons to an atomic nucleus. Radioactive decay takes place inside Earth (among other places), while nuclear fusion is the source of the Sun's power.

Nuclear fusion involves the release of huge amounts of energy. On Earth, scientists have been able to bring about uncontrolled nuclear fusion in the form of the so-called hydrogen bomb, which is actually a "fusion bomb." They have yet to succeed in creating controlled nuclear fusion. If and when they do, it would provide a safe, clean source of almost limitless power and probably would constitute the greatest scientific or technological discovery since fire.

On the Sun, nuclear fusion has been taking place, and will continue to do so, for a long, long time. The 92 naturally occurring elements of the universe are the result of fusion reactions, meaning that all that we see around us was once part of a star. This represents a major break with the ancient belief that Earth is made of fundamentally different substances than are the bodies of space (see Earth, Science, and Nonscience). In fact, our world and everything in it—including our own bodies—is truly "the stuff of stars."

The Moon and Earth

In comparison to the Sun, the Moon is altogether less remarkable. Below, we review some statistics about the sizes of each, but as every elementary-school student today knows, the Sun is much, much larger and exerts far more impact on the fate of the solar system—including Earth. The Moon does not even have its own energy sources: its light comes from the Sun, and the absence of an atmosphere, of volcanic activity, or even of a significant magnetic field makes it a very dull place indeed.

Yet the Moon has inspired at least as much fascination among humans over the ages as has the Sun. There is its physical beauty, though comparisons with the Sun are hardly fair, since we cannot look at the Sun without damage to our eyes. There is also its influence on earthly cycles ranging from the tides to the months themselves, though some claims of lunar influence have little basis in fact. During the Middle Ages, many believed that the Moon caused madness, a superstition still reflected in our word lunacy.

Still, humans have long associated a spirit of mystery with the Moon, in part because of its ever-changing appearance and in part because it has always showed just one side to Earth. (We discuss the reason why later.) Only in 1959, when the Soviet space probe *Luna* traveled to the "dark side of the Moon," did scientists gain a glimpse of it. Unmanned and later manned journeys, which culminated with the U.S. Moon landing in 1969, also changed astronomers' understanding of the Moon's origins.

THE "BIG WHACK." One of the curious things about the Moon is its size in relation to Earth. Nowhere in the universe is there such a small size differential between a satellite

and the planet around which it orbits, the only possible exception being Pluto and its moon, Charon. Because our Moon is so close in size to Earth, scientists once speculated that they might have shared origins, and this speculation informed several theories concerning the formation of the Moon.

According to the fission theory, the Moon was a piece of Earth that had been torn away, perhaps from the Pacific basin. The simultaneous creation theory likewise depicted Earth and the Moon as sharing origins, but in this case they literally had been formed together from the same materials. Finally, there was the capture theory, which, in contrast to the others, assumed quite different origins for the two bodies: the Moon had formed somewhere else in the solar system and had been captured by Earth's gravitational field after it wandered too close to the planet.

As it turned out, the capture theory was closest to the theory accepted today, though it was discarded along with the other two on the basis of data brought back from the Apollo Moon landings. According to the giant impact theory, sometimes called the Big Whack model or the ring ejection theory, at a young age Earth was sideswiped by a celestial object as large or larger than Mars. As a result of that collision, a ring of crustal matter was spewed into space, and over time the matter in this ring agglomerated to form the Moon.

Vital Statistics of the Sun and Moon

The Moon is about 240,000 mi. (385,000 km) from Earth, meaning that it takes about 1.25 seconds for its light to reach Earth. By contrast, the Sun's distance from Earth is so great that it takes eight minutes for sunlight to reach our planet, even though light travels through space at the speed of about 186,000 mi. (299,339 km) per second.

The distance between Earth and the Sun is the basis for the astronomical unit (AU), a figure used for measuring the distance between bodies in the solar system. Equal to the average distance from Earth's center to the center of the Sun, an AU is designated $1.49597870691 \times 10^8$ km, or approximately 92,955,807 mi. Usually we think of the solar system as the area encompassed by the orbit of the most remote planet, Pluto, but that is only 39.44 AU, a tiny figure compared with the diameter of the realm within the Sun's gravitational pull, which is a staggering 100,000 AU.

Volume and mass. The Sun itself has a diameter of about 856,000 mi. (1,392,000 km), meaning that the distance across it is about 109 times that of Earth's diameter. Another way to consider that figure is this: if one were to draw a circle as big as the Sun around Earth, the edge of that circle would be about twice as far away as the Moon. The Sun's volume is so great that about 1.3 million Earths could fit inside it, and its mass is about 300,000 times that of Earth. In fact, it accounts for about 99.8% of the mass of the entire solar system.

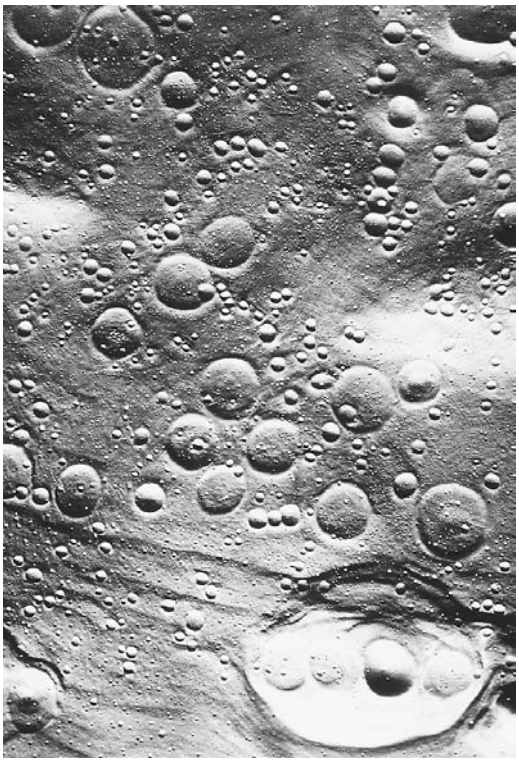
By contrast, the Moon has a diameter of only about 2,160 mi. (3,475 km), a little less than the distance from New York to Los Angeles. Its mass is a little more than 1% of Earth's, and as a result, its gravitational pull is too small to retain the gases that make up the atmosphere. That small mass, combined with an imbalance in its distribution, explains why the Moon shows only one face to Earth. The side of the Moon facing Earth is of greater mass than the other side and is therefore more strongly attracted by Earth's gravitational force. The result is a phenomenon called gravitational locking, whereby the Moon rotates on its axis at exactly the same rate as it travels around Earth—once ever 29.5 days.

Clearly, the Moon is tiny in both volume and mass, and were it as far away as the Sun, we would hardly pay it notice. Yet it should be pointed that even the Sun itself, while remarkable in our own solar system, is far from a standout in the universe as a whole. It is a youngish star, of average size, and not all that different from billions of other stars throughout the cosmos. It is not even unique in being the only star with its own solar system. In 1999 astronomers discovered an entire solar system some 44 light-years from Earth, in which three large planets were found to be circling the star Upsilon Andromedae.

REAL-LIFE APPLICATIONS

Energy, Temperature, and Composition of the Moon

Of course, the area in which the Sun and Moon differ most significantly is in terms of the energy they possess, which, in turn, affects both their



The Moon's surface is pockmarked with craters, showing its vulnerability to damage caused by particles from space. *(© NASA/Photo Researchers. Reproduced by permission.)*

temperature and the composition of each body. With regard to the Moon's temperature, little need be said, since it is entirely a function of the Moon's exposure (or lack of exposure) to heat from the Sun. On the Moon figures range from 280°F (138°C) to –148°F (–100°C), with a mean temperature of –10°F (–23.33°C).

As for the Moon's composition, it has similarities to and differences from that of Earth, and both these similarities and differences are instructive. The internal composition of the Moon is such that it often is treated along with the terrestrial planets. In addition, it is not much smaller than the smallest terrestrial planet, Mercury. But whereas Mercury has a proportionally large, extremely hot core, the Moon's core is much smaller in proportion to its total size and much cooler. In all likelihood it is not even molten, or only a portion of it is.

It appears that the Moon has an internal structure not dissimilar to that of Earth—that is, a crust, mantle, and core. The materials that make up the Moon, however, are quite different. Aluminum, calcium, iron, magnesium, titanium, potassium, and phosphorus have been found on the Moon, but it seems bereft of organic compounds, indicating that life never existed there. Moon rocks are primarily of basalt, or hardened lava, and breccia, soil, and rock fragments that have melted together.

The formation of these rocks must have occurred a long, long time ago, because the Moon has not had volcanic activity for several billion years. Thus, it is almost entirely "dead," lacking even a magnetic field of any significance. Moon rocks have only the faintest magnetic field, suggesting the absence of a significant molten core, which is what gives Earth its own magnetism. From the traces of magnetism found in these rocks, it is possible that the Moon had a magnetic field of some significance at one time, but that time is long past.

THE VULNERABLE MOON. Owing to the Moon's lack of sufficient gravitational force, it retains no atmosphere, and this means that it is completely vulnerable to particles reaching it from space. Early in its life, the Moon was subjected to a 700-million-year-long meteor shower that formed its craters. The damage from these showers was so great that it melted the Moon's crust, and eventually lava from the lunar interior surfaced to fill in cracks made by the meteorites.

In 1609 the Italian astronomer Galileo Galilei (1564–1642), the first scientist to gaze at the Moon through a telescope, observed dark patches that looked to him like bodies of water. He named these patches *seas,* a term that has remained in use among lunar cartographers, though Galileo's "seas" long ago were identified as dark spots made by cooling lava in the cracked surface.

As it is vulnerable to particles from space, the Moon also is susceptible to dramatic temperature changes brought about by the presence or absence of sunlight. For this reason, parts of the lunar surface are extremely hot at certain times, while other portions have never been penetrated by sunlight and are almost inconceivably cold.

Humans on the Moon

One such cold spot is at the Moon's south pole, in a basin carved out by an asteroid. There, temperatures are as low as –387°F (–233°C), within 40°C of absolute zero, or the temperature at which all molecular motion virtually ceases. By

contrast, Pluto, which is so far from the Sun that the great star appears merely as a bright dot from there, has an average surface temperature that is warmer by 8°C. Yet in this inhospitable spot on the lunar surface, the U.S. probe *Lunar Prospector* in 1998 found something quite surprising: water.

Mixed in with dirt in the South Pole–Aitken Basin are ice crystals, which scientists speculate make up about 10% of the material in the surrounding area. Apparently moisture residue from comets that struck the Moon over the past three billion years, the ice offers intriguing possibilities. If a cost-effective method for extracting ice from the soil can be developed, colonization and exploration of the Moon may become a reality.

MOON LANDINGS. For now, however, human presence on the Moon is more a thing of the past than of the future. The first man-made spacecraft to visit the Moon was the Soviet *Luna 2* in 1959, and seven years later, *Luna 9* became the first such craft to land on the lunar surface. Its landing dispelled long-held fears that the Moon was awash in thick layers of dust; in fact, the lunar surface is a grayish soil, primarily composed of rock fragments, from 5 ft. to 20 ft. (1.5 m to 6 m) deep.

Though the Soviets were the first to reach the Moon in unmanned craft, the United States was the first (and so far the only) nation to put a man on the Moon. On July 20, 1969, in one of the most dramatic events of human history, the U.S. astronauts Neil Armstrong (1930–) and Edwin ("Buzz") Aldrin (1930–) walked on the lunar surface while Michael Collins (1930–) piloted *Apollo 11* in its orbit around the Moon.

Photographs from the Moon landing show the American flag extended, as though waving in a breeze as it would on Earth, but it actually was held in place mechanically, since there is no wind on the Moon. Aldrin and Armstrong demonstrated one of the most dramatic differences between the Moon and Earth: a decrease in weight. A man who weighs 200 lb. (90.72 kg) on Earth would weigh 33.04 lb. on the Moon and would therefore be much easier to lift. But he would be no easier to push from side to side, because his mass would not have changed.

Weight is the product of mass multiplied by the rate of gravitational acceleration and is therefore dependent on the gravitational force of the celestial body on which it is measured. Mass, on the other hand, does not vary anywhere in the universe. Thus, although 33.04 lb. is equal to 14.99 kg on Earth, the hypothetical astronaut described here would still have a mass of 90.72 kg.

Physicists had long known these facts about weight and mass, but footage of Armstrong and Aldrin bouncing around on the lunar surface provided a much more vivid demonstration. As it turned out, however, their foray to the Moon was the beginning of an all-too-brief chapter. Over the next three years, the United States conducted five more lunar landings as well as the failed 1970 mission designated *Apollo 13* (portrayed in the 1995 movie of that name), which never landed due to an onboard explosion. The last Moon mission took place in 1972, and soon afterward America was thrown into a recession spawned by the 1973 oil crisis. The next sustained effort at space flight, which began with the launch of the space shuttle in 1981, had an entirely different mission and destination—one that lay well within Earth's gravitational field.

SOLAR ENERGY, TEMPERATURE, AND COMPOSITION

Needless to say, there never will be any space missions, manned or otherwise, to the Sun. Spacecraft have passed close to Mercury, but as for the Sun, even its corona, or outermost atmospheric layer, has a temperature of 2,000,000 on the Kelvin scale of absolute temperature, or 3,599,541°F.

The Sun could not be more different from the Moon, most notably in terms of energy and temperature. It should be noted, however, that the Sun's temperature does not increase uniformly from the corona to the core. The "coolest part," at 5,800K (9,981°F), is the photosphere, a layer some 300 mi. (480 km) thick that constitutes the visible surface of the Sun. Above it, temperatures rise through the chromosphere, which is about 1,600 mi. (2,560 km) thick, becoming hotter still in the corona. Scientists do not understand the reasons for this temperature rise at the outer surface of the Sun.

Less surprising is the continued increase of temperature beneath the photosphere. The deeper inside the Sun, the higher the temperatures, until it reaches a staggering 15,000,000K (27,000,000°F) at the core. It is so hot there that not even atoms can exist; instead, the Sun's core is made up of subatomic particles—specifically, protons and electrons. Heat and movement are

directly related in physics, and these particles are moving very fast—so fast that nuclear fusion can and does occur when these particles smash together.

NUCLEAR FUSION IN THE SOLAR CORE. When four protons fuse and absorb two electrons, amazing things happen. The result is the creation of a helium nucleus, whose mass is slightly smaller than the combined mass of the separate particles. Where did that "missing" mass go? It was converted to energy—an amount of energy that is staggering when multiplied by the large numbers of hydrogen atoms being converted to helium at any given moment.

That, in essence, is how the Sun creates energy—by converting hydrogen to helium. This energy is radiating from the Sun in electromagnetic waves at an amazing rate every second, and eventually it will be used up. Long before that happens, however, the Sun will begin to expand and cool. "Cooling," of course, is a relative term; this expanding Sun, a red giant, will burn up Earth even as it absorbs Mercury entirely. Then, when it has used up all its hydrogen, nothing will remain but a glowing core called a white dwarf.

There is no need to worry, however, because the events described will not happen anytime soon. The Sun has about as much life left in it as the amount of time it has lasted so far—approximately five billion years, or longer than Earth has existed. Given the fact that about 4.96 million tons (4.5×10^6 metric tons) of hydrogen are converted to helium every second, this gives some idea of the vast energy reserves on the Sun.

THE SUN'S ENERGY AND EARTH. Sunlight is more than just light, though that alone is a marvelous thing. The rays projected by the Sun are electromagnetic energy, of which visible light is only a small part. Also contained in the electromagnetic spectrum are long waves, short waves, and microwaves (including those used for transmitting radio and television signals); infrared and ultraviolet light; and x rays and gamma rays. Solar energy travels to Earth by means of radiation, a form of heat transfer that, unlike conduction or convection, requires no physical medium such as air. It can move through the vacuum of space to Earth's atmosphere, where a portion of it is absorbed and becomes the fuel that powers spaceship Earth.

It is a measure of the Sun's vast energy that Earth receives only 0.00000005% of its total output at any given moment. Of that small fraction (equal to one part in two billion), a much smaller portion makes it through Earth's atmosphere—yet that is enough to light the world and to facilitate the myriad other functions, such as photosynthesis, for which we depend on the Sun. Many effects of the Sun's light and energy are less than desirable, of course: sunburns and sometimes even tans, bleaching of materials exposed to light for too long, temporary blindness caused by gazing at the Sun or even at something reflecting it, and so on. These effects, too, attest to the Sun's awesome power.

The Sun makes possible the operations of three of four Earth systems and indirectly affects the fourth (see Earth Systems). The hydrosphere and atmosphere are both affected, for instance, by the evaporation of water for eventual precipitation, a process powered by the Sun. Likewise, the biosphere could not exist without photosynthesis and the other biological processes dependent on sunlight. Even the geosphere, though not directly powered by the Sun, is influenced by Sun-powered phenomena from the other three spheres.

Curious Solar Phenomena

Even traveling at the speed of light, a photon takes nearly 30,000 years to travel from the center of the Sun to the corona. If it were in a vacuum, it could make the journey in about four seconds, but it continually bumps into other particles, and this slows it down (to put it mildly). Once it finally escapes the solar surface, it travels rather quickly, transmitting the Sun's light to the solar system.

When that light reaches Earth's atmosphere, it creates a number of strange optical effects. One of the best known is the rainbow, produced by the refraction, or bending, of light inside a raindrop. Because the colors of the visible spectrum are bent at different angles, they disperse as though in a prism; after being refracted a second time by the surrounding air, the billions of raindrops that fill the atmosphere after a storm produce a brilliant band of light.

When sunlight strikes oxygen or nitrogen, the two most significant elements in our atmosphere, the shorter wavelengths of light—green, blue, and violet—are the ones reflected. When



The aurora borealis, or northern lights. This phenomenon is caused by solar particles drawn to Earth's atmosphere, where they collide with oxygen and nitrogen molecules and become electrically charged, taking on a colored glow. *(© Michael Giannechini/Photo Researchers. Reproduced by permission.)*

these wavelenths combine, they appear bluish. The combination of light and differing temperatures on the ground produces a mirage, while ice crystals in the air may bring about haloes around the Sun or Moon and, in some cases, a sun dog, a reflected image of the Sun.

THE NORTHERN LIGHTS. One of the most breathtaking displays of atmospheric

optical phenomena are auroras (or aurorae), natural fireworks that appear in the night sky. Visible in the northern United States and Canada, the auroras there are known as aurora borealis, or northern lights. A similar phenomenon occurs in the Southern Hemisphere, where it is called the southern lights, or aurora australis.

The source of the auroras is a stream of particles, called the *solar wind,* that emanates from the Sun. The solar wind is a consequence of the extreme heat on the Sun's surface, which causes atoms there to move so rapidly that even the enormous gravitational force of the Sun itself cannot hold them. Solar particles pass through the entire solar system and out to space beyond, but few of them reach Earth's atmosphere, because they are deflected by the planet's magnetic field.

The particles that cause auroras are electrons that instead of being deflected, are drawn toward Earth's polar regions. Two great rings of charged particles, called the Van Allen belts, are located high above each polar region, and they catch the majority of charged particles flowing toward them from the northern and southern hemispheres, respectively. The Van Allen belts cannot trap all the charged particles, however, and some enter the atmosphere, where they collide with oxygen and nitrogen molecules at about 50 mi. to 600 mi. (80 km to 1,000 km) above sea level. Some of these molecules become electrically charged and take on a colored glow. At higher levels oxygen glows red, while oxygen at lower levels is yellowish-green. Nitrogen glows blue.

SUNSPOTS AND THE SOLAR ACTIVITY CYCLE. Though auroras are visually remarkable, a more significant solar phenomenon is the sunspot. Sunspots are cooler regions—many of them vast in size—on the photosphere. They tend to be about 2,700°F (1,500°C) cooler than the surrounding areas, and for this reason they appear darker.

Sunspots seem to occur in 11-year cycles—a period known as a solar activity cycle—and are the result of strong magnetic fields. The latter, in turn, result from something called differential rotation: the Sun's equator rotates once every 26 days, whereas its poles rotate every 36 days, resulting in massive twisting of magnetic fields. This can produce anomalies such as sunspots, which disrupt radio communications on Earth.

Other solar anomalies, such as prominences, or hot spots formed by magnetic loops in the Sun's atmosphere, also follow the 11-year solar activity cycle. Actually, the cycle as it is known and measured *today* is about 11 years long. Its length seems to have varied over time, producing past changes in global temperature: the shorter the cycle, the warmer the temperatures on Earth.

The Sun, Moon, and Events on Earth

As noted earlier, the Sun and Moon have long inspired awe in humans, and in this the Moon has been a more than equal partner. Prehistoric and ancient humans regarded both lunar eclipses, in which Earth's shadow covers the Moon, and solar eclipses, in which the Moon comes between Earth and the Sun, as portents from the gods. From at least the era of the Babylonians onward, the Sun and Moon played complementary roles in marking time.

The marking of time according to the Sun relies on an objective reality, rather than a mere human construct. The year, which involves a complete cycle of seasons, is based on the amount of time Earth takes to revolve around the Sun. During this time, the planet also moves on its axis, causing the changes in orientation that bring about the seasons. Likewise a day is an objective reality, being the amount of time it takes Earth to revolve on its axis.

The month and week, on the other hand, relate to the phases of the Moon, which are themselves dependent on the Moon's position relative to Earth and the Sun. A lunar cycle lasts about 29.5 days, and this became the basis for the month, which lasts from 28 to 31 days. Within that lunar cycle are four phases—new, first quarter, full, and last quarter—which eventually became the basis for the idea that a month has about four seven-day weeks.

DAYS OF THE WEEK. Until about 1500, people thought of the Sun and Moon as two of the seven "planets" (including the five planets visible with the naked eye) that supposedly revolved around Earth. They further related these "planets" to the days of the week. As a result, virtually every culture that speaks a Euro-

KEY TERMS

ABSOLUTE ZERO: The temperature at which all molecular motion virtually ceases.

ASTRONOMICAL UNIT (AU): A figure equal to the average distance from Earth's center to the center of the Sun. The SI figure for an AU, adopted in 1996, is equal to $1.49597870691 \times 10^8$ km, or approximately 92,955,807 mi.

ATMOSPHERE: In general, an atmosphere is a blanket of gases surrounding a planet. Unless otherwise identified, however, the term refers to the atmosphere of Earth, which consists of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon, which together comprise 0.07%.

ATOM: The smallest particle of an element, consisting of protons, neutrons, and electrons. An atom can exist either alone or in combination with other atoms in a molecule.

ATOMIC MASS UNIT: An SI unit (abbreviated amu), equal to 1.66×10^{-24} g, for measuring the mass of atoms.

ATOMIC NUMBER: The number of protons in the nucleus of an atom. Since this number is different for each element, elements are listed on the periodic table in order of atomic number.

AVERAGE ATOMIC MASS: A figure used by chemists to specify the mass—in atomic mass units—of the average atom in a large sample.

BIOSPHERE: A combination of all living things on Earth—plants, mammals, birds, reptiles, amphibians, aquatic life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed. Typically, after decomposing, a formerly living organism becomes part of the geosphere.

CORE: The center of Earth, which appears to be of molten iron. For terrestrial planets in general, *core* refers to the center, which in most cases is probably molten metal of some kind.

COSMOLOGY: The study of the origin, structure, and evolution of the universe.

COSMOS: The universe.

ELECTROMAGNETIC ENERGY: A form of energy with electric and magnetic components, which travels in waves.

ELECTROMAGNETIC SPECTRUM: The complete range of electromagnetic waves on a continuous distribution from a very low range of frequencies and energy levels, with a correspondingly long wavelength, to a very high range of frequencies and energy levels, with a correspondingly short wavelength. Included on the electromagnetic spectrum are long-wave and short-wave radio; microwaves; infrared, visible, and ultraviolet light; x rays, and gamma rays.

ELECTRON: A negatively charged particle in an atom, which spins around the nucleus.

ELEMENT: A substance made up of only one kind of atom. Unlike compounds, elements cannot be broken chemically into other substances.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live

KEY TERMS CONTINUED

and which provides them with most of their food and natural resources.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

INERTIA: The tendency of an object in motion to remain in motion and of an object at rest to remain at rest.

ION: An atom that has lost or gained one or more electrons and thus has a net electric charge.

ISOTOPES: Atoms that have an equal number of protons, and hence are of the same element, but differ in their number of neutrons. This results in a difference of mass. An isotope may be either stable or radioactive.

JOVIAN PLANETS: The planets between Mars (the last terrestrial planet) and Pluto, all of which are large, low in density, and composed primarily of gases.

KELVIN SCALE: Established by William Thomson, Baron Kelvin (1824–1907), the Kelvin scale measures temperature in relation to absolute zero, or 0K. (Note that units in the Kelvin system, known as Kelvins, do not include the word or symbol for "degree.") The Kelvin scale, which is the system usually favored by scientists, is directly related to the Celsius scale; hence Celsius temperatures can be converted to Kelvin by adding 273.15.

LIGHT-YEAR: A unit of distance used by astronomers for measuring the extremely large expanses of space. Equal to the distance light travels in a year, a light-year is $9.460528405 \times 10^{12}$ km, or approximately 5.88 trillion mi.

LITHOSPHERE: The upper layer of Earth's interior, including the crust and the brittle portion at the top of the mantle.

MANTLE: The layer, approximately 1,429 mi. (2,300 km) thick, between Earth's crust and its core. In reference to the other terrestrial planets, *mantle* simply means the area of dense rock between the crust and core.

MASS: A measure of inertia, indicating the resistance of an object to a change in its motion. (By contrast, weight—which people tend to think of as analogous to mass—is a measure of gravitational force, or mass multiplied by the acceleration due to gravity.)

NEUTRON: A subatomic particle that has no electric charge. Neutrons are found at the nucleus of an atom, alongside protons.

NUCLEAR FUSION: A nuclear reaction that involves the joining of atomic nuclei.

pean language—not only in Europe itself but also among former European colonies in the Americas, Africa, Asia, and the Pacific—refers to the first day of the week as the Sun's day and the second as the Moon's day.

Today, in countries that speak Romance languages, or languages derived from Latin (most notably Italian, French, Spanish, and Portuguese), variations on the original Latin names remain in use: Domingo and Lunes in Spanish, for instance, or Dimanche and Lundi in French. Germanic languages adopted the ideas of the Latin day names, for the most part, but translated them into their own tongues: hence, Sonntag

KEY TERMS CONTINUED

NUCLEUS: The center of an atom, a region where protons and neutrons are located and around which electrons spin.

ORGANIC: At one time, chemists used the term "organic" only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of calcium carbonate (limestone) and oxides, such as carbon dioxide.

PERIODIC TABLE OF ELEMENTS: A chart that shows the elements arranged in order of atomic number, along with chemical symbol and the average atomic mass for that particular element.

PHOTON: A particle of electromagnetic radiation carrying a specific amount of energy.

PLANETARY SCIENCE: The branch of the earth sciences, sometimes known as planetology or planetary studies, that focuses on the study of other planetary bodies. This discipline, or set of disciplines, is concerned with the geologic, geophysical, and geochemical properties of other planets but also draws on aspects of astronomy, such as cosmology.

PROTON: A positively charged particle in an atom.

RADIATION: The transfer of energy by means of electromagnetic waves, which require no physical medium (for example, water or air) for the transfer. Earth receives the Sun's energy, via the electromagnetic spectrum, by means of radiation.

RADIOACTIVITY: A term describing a phenomenon whereby certain materials are subject to a form of decay brought about by the emission of high-energy particles or radiation. Forms of particles or energy include alpha particles (positively charged helium nuclei); beta particles (either electrons or subatomic particles called positrons); or gamma rays, which occupy the highest energy level in the electromagnetic spectrum.

REFRACTION: The bending of light as it passes at an angle from one transparent material into a second transparent material. Refraction accounts for the fact that objects under water appear to have a different size and location than they have in air.

SI: An abbreviation of the French term *Système International d'Unités,* or "International System of Units." Based on the metric system, SI is the system of measurement units in use by scientists worldwide.

TERRESTRIAL PLANETS: The four inner planets of the solar system: Mercury, Venus, Earth, and Mars. They are all small, rocky, dense, have relatively small amounts of gaseous elements, and are composed primarily of metals and silicates. Compare with Jovian planets.

and Montag in German, or Sunday and Monday in English.

CYCLES AND TIDES. One reason the ancients respected the Moon as much as the Sun is that it seemed to affect many aspects of human life—as indeed it does. Medieval ideas about "lunacy" were themselves more than a little off-kilter, and the belief that the Moon affects female menstrual cycles has come under significant challenge. Nevertheless, the Moon does seem to have some effect on human biological cycles.

The human circadian rhythm, or cycle of sleep and wakefulness, stretches over a period of

25 hours, meaning that a person living in a cave without any exposure to sunlight would eventually assume a 25-hour-a-day schedule. The reason for this disparity between the human circadian cycle and the length of a solar day is not known, but it is possible that the circadian cycle is based on the length of a lunar day, or the interval between periods of time when the Moon appears in the sky over a given spot on Earth. Because the Moon is moving even as Earth is rotating, this span of time is not 24 hours, the interval it takes Earth to rotate on its axis, but 24 hours and 50 minutes.

It is also more than an old wives' tale that people behave strangely around the time of a full moon: in fact, more deaths and accidents do occur at that point in the monthly cycle. One of the most significant lunar-influenced cycles, however, is not monthly but semidiurnal, or twice daily. These are the cycles of Earth's tides, brought about by the gravitational attraction exerted on Earth by the nearest significant celestial object. (The Sun also affects tides, but much less so because of its greater distance from Earth.) Though the Moon's effect on tides has been known since ancient times, the ancients did not understand the gravitational nature of its attraction, which actually causes a bulge to appear in the oceans.

In fact, two bulges appear, one in the oceans on the side of Earth nearest the Moon and one on the opposite side. The latter is also a result of the Moon's gravitation, which pulls Earth in the other direction, thus drawing the solid earth away from the water. These bulges are known as high tide, and the resulting displacement of water causes a low tide. In most places on Earth, tides are semidiurnal, meaning that there are two full cycles of high and low tide per day. Sometimes these variations can be very great, as at the Bay of Fundy in Canada, where the tidal range is as large as 46 ft. (14 m).

The tides are related closely to phases of the Moon, or, to put it another way, they are affected by the alignment between the Moon and the Sun. At the new moon, the Moon is between Earth and the Sun, and during a full moon, the Moon is on the other side of Earth from the Sun. (Because of a 20° angle between Earth's orbit and that of the Moon, Earth rarely casts a shadow on a full moon, except in the case of a lunar eclipse.) In the new-moon and full-moon phases, the Moon and Sun are aligned, and this combination of lunar and solar gravitation produces strong spring tides every 14 days. On the other hand, when the Moon and Sun are at angles to each other—during the first quarter and last quarter, sometimes known as half-moons—it produces a much weaker neap tide.

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SCIENCE OF EVERYDAY THINGS

Real-Life Earth Science

GEOLOGY

Historical Geology

Historical Geology
Geologic Time
Stratigraphy
Paleontology

Physical Geology

Minerals
Rocks
Economic Geology

HISTORICAL GEOLOGY

CONCEPT

Geologists are concerned primarily with two subjects: Earth's physical features and the study of the planet's history. These two principal branches of geology are known, appropriately enough, as physical geology and historical geology. Today they are of equal importance, but in the early modern era, geologists were most focused on topics related to historical geology, in particular, Earth's age and the means by which Earth was formed. This debate pitted adherents of religion, which seemed to require a very young Earth, against adherents of science. A breakthrough came with the introduction of uniformitarianism, a still-influential principle based on the idea that the geologic processes at work today have always been at work. Opposing uniformitarianism was catastrophism, or the idea that Earth was formed in a short time by a series of cataclysmic events. Discredited at the time, catastrophism later gained acceptance, though this did not lead to support for the concept of a young Earth. In fact, the planet is very old—so old that all of human history is almost inconceivably short in comparison.

HOW IT WORKS

Explaining Origins

For thousands of years, humans were content to rely on religiously inspired stories, rather than scientific research, to provide an explanation regarding Earth's origins. This topic, along with the scientific challenge to those early accounts of Earth's formation, is discussed in considerable detail within the essay Earth, Science, and Nonscience. Other aspects of the subject, particularly the challenge to mythological explanations put forward by earth scientists in modern times, are examined here.

All religious explanations of the planet's origins can be called myths, which is not necessarily a pejorative term: a myth is simply a story to explain how something came into being. So pervasive are myths about geology that a term, *geomythology,* has been coined to identify such myths. Geomythology in particular and mythology in general stand in sharp contrast to scientific explanations derived by using the scientific method of observation, hypothesis formation, testing of hypotheses, and the development and testing of theories.

CONTRASTING SCIENCE AND RELIGIOUS GEOMYTHOLOGY. Science and myth have in common the aim of explaining how things came to be, but the means by which they reach that explanation are quite different. So, too, are the reasons that drive science on the one hand and religion or myth on the other in seeking to develop such an explanation.

The most famous of all religious explanations of Earth's origins, of course, is that found in the biblical book of Genesis. Probably written in the latter part of the second millennium B.C., it offered a compelling story of creation that virtually defined the Western view of Earth's origins for more than 1,500 years, from about A.D. 300 to the beginning of the nineteenth century. Its purpose, of course, was not scientific, and it was not written as the result of research; rather, the Genesis account depicts nature as a vast stage on which a cosmic drama of love, sin, redemption, and salvation has been played out over the ages.

By contrast, the scientific search for Earth's origins is driven merely, or at least primarily, by curiosity to explain how things came to be as they are. Scientists certainly have their biases and are just as capable of error as anyone, yet at least they have a standard in the form of the scientific method. If a scientist's findings, and the resulting theory, withstand the rigorous testing required by the scientific method, the theory is rewarded with increasing acceptance and new research designed to test further its ability to explain the world. If the theory fails those tests, its adherents may hold on to it for a time, but eventually they die off, and the theory is discarded. On the other hand, adherence to the religious explanation of Earth's origins has proved more intractable, as we shall see.

The Religious War Concerning Earth's Origins

The great Italian artist and scientist Leonardo da Vinci (1452–1519) was among the first Western thinkers to speculate that fossils might have been made by the remains of long-dead animals. This was a daring supposition to make in the Renaissance, and it would become even more daring to uphold such an idea in the centuries that followed. The concept of fossils seemed to imply an Earth older than the biblical account suggested, and with the Catholic Church under attack by the forces of religious reformation (i.e., Protestantism) and other forms of "heresy," church leaders became less and less inclined to tolerate any deviation from orthodoxy.

The ecclesiastical view of Earth's history reached a sort of extreme in the seventeenth century, with the Irish bishop James Ussher (1581–1656). The New Testament contains a thorough accounting of Jesus' lineage, both through his mother and his earthly father, Joseph, all the way back to the time of Adam. Jesus was descended from David, whose lineage is provided in the Old Testament, complete with each ancestor's life span and the age at which he fathered a successor in the Davidic line of descent. From these figures, Ussher concluded that God finished making Earth at 9:00 A.M. on Sunday, October 23, 4004 B.C. Accepted by the Church, Ussher's calculation gave the idea of a very young Earth an aura of "scientific" justification.

Ironically, one of the first scientists to discover evidence that pointed toward an extremely old Earth was also a minister, the English astronomer Henry Gellibrand (1597–1636). While researching Earth's magnetic field, Gellibrand discovered that the field had changed over time (as indeed it has—for more on this subject, see Geomagnetism). This was one of the first indications that the planet's history can be studied scientifically, even though humans have no direct information regarding the origins of Earth.

Early Stratigraphic Studies

After Gellibrand came the Danish geologist Nicolaus Steno (1638–1687), who studied the age of rock beds. Thus was born the concept of stratigraphy, or the study of rock layers beneath Earth's surface, which revealed a great deal about the planet's age. (See Stratigraphy, which discusses many topics related to historical geology.) Along with the English physicist Robert Hooke (1635–1703) and others, Steno also became one of the first thinkers to confront the possibility that Earth must be much more than 6,000 years old.

During the eighteenth century, the German geologist Johann Gottlob Lehmann (1719–1767) built on ideas introduced by Steno concerning the formation of rock beds. Lehmann put forward the theory that certain groups of rocks tend to be associated with each other and that each layer of rock is a sort of chapter in the history of Earth. Aspects of Lehmann's theory were incorrect, but the general principle marked an advancement over previous ideas in geology and helped point the way toward a new view of the earth sciences.

Previously, geologic studies had tended to be qualitative and descriptive, meaning that earth scientists used very generalized terminology and failed to possess a grasp of larger issues. Thanks to Lehmann and others who followed him, the earth sciences became more truly quantitative and predictive, offering explanations of what had happened in the past, along with justifiable theories concerning what might happen in the future.

The German geologist Abraham Gottlob Werner (1750–1817) put forward a theory that was largely incorrect, yet one that nevertheless advanced the earth sciences. His "neptunist" theory was based on the idea that water had been the main force in shaping Earth's surface. Though this theory was not accurate, his idea was significant, because it constituted the first well-ordered geologic theory of Earth's origins and early history. At the same time, that history was turning out to be very long indeed.



Leonardo da Vinci was the first to suggest that fossils are long-dead animal remains, implying that Earth is older than the biblical account in Genesis would suggest. *(AP/Wide World Photos. Reproduced by permission.)*

Religion and Earth's Age

In 1774 the French mathematician Georges-Louis Leclerc, Comte de Buffon (1707–1788), applied new scientific ideas to the study of Earth and estimated its age at 75,000 years. Privately he admitted that he actually thought Earth was billions of years old but did not think that such a figure would be understood. At the time, after all, the concept of a "billion" was hardly a familiar one, as it is today. More important, the idea of

Earth being that old was shocking and downright frightening to people who accepted a strict interpretation of the biblical account.

In an earlier century, the Italian astronomer Galileo Galilei (1564–1642) had been forced, on pain of death, to recant his support for the Polish astronomer Nicolaus Copernicus's (1473–1543) discovery that Earth is not the center of the universe. In Buffon's day, by contrast, few Europeans faced such dire threats for endorsing apparently unbiblical ideas. A scientist could still lose his job for supporting the wrong principles, and thus Buffon had to renounce his position on threat of losing his post at the University of Paris.

AN ATHEISTIC REACTION. Other forces were at work in the sciences during the eighteenth century, and some were openly hostile to religious belief. An extreme example was the French physician and philosopher Julien de La Mettrie (1709–1751), a leading figure in the mechanist school of the biological sciences. La Mettrie maintained that humans are essentially a variety of monkey, to whom they were superior only by virtue of possessing the power of language. Moving far beyond the territory of science itself, he also taught that atheism is the only road to happiness and that the purpose of human life is to experience pleasure.

In the physical sciences, an interesting example of reaction to religious belief can be found in the case of the French mathematician Pierre Simon de Laplace (1749–1827). Like those of La Mettrie, Laplace's aims were not purely scientific; instead, he envisioned himself as a warrior against religious belief. Correctly enough, Laplace maintained that the origins of the universe as well as its workings could be explained fully without any reference to God. He also introduced a highly influential theory, widely accepted today, that the solar system originated from a cloud of gas. (See the entries Planetary Science and Sun, Moon, and Earth.)

Like La Mettrie, Laplace took his ideas far beyond their justifiable purview in the realm of science, however, wielding them as a sword in a religious war. Laplace maintained that because it was possible to discuss the origins of the cosmos without reference to God, there must be no God—which is far from a logically necessary conclusion. Misguided as La Mettrie's and Laplace's atheistic crusades may have been, they are historically understandable: in France, far more than anywhere in western Europe except perhaps Spain, the Church had come to be seen as a force of political oppression, allied as it was with the French royalty. It is no wonder, then, that the French Revolution of 1789 was directed as much against the Church as against the king.

REAL-LIFE APPLICATIONS

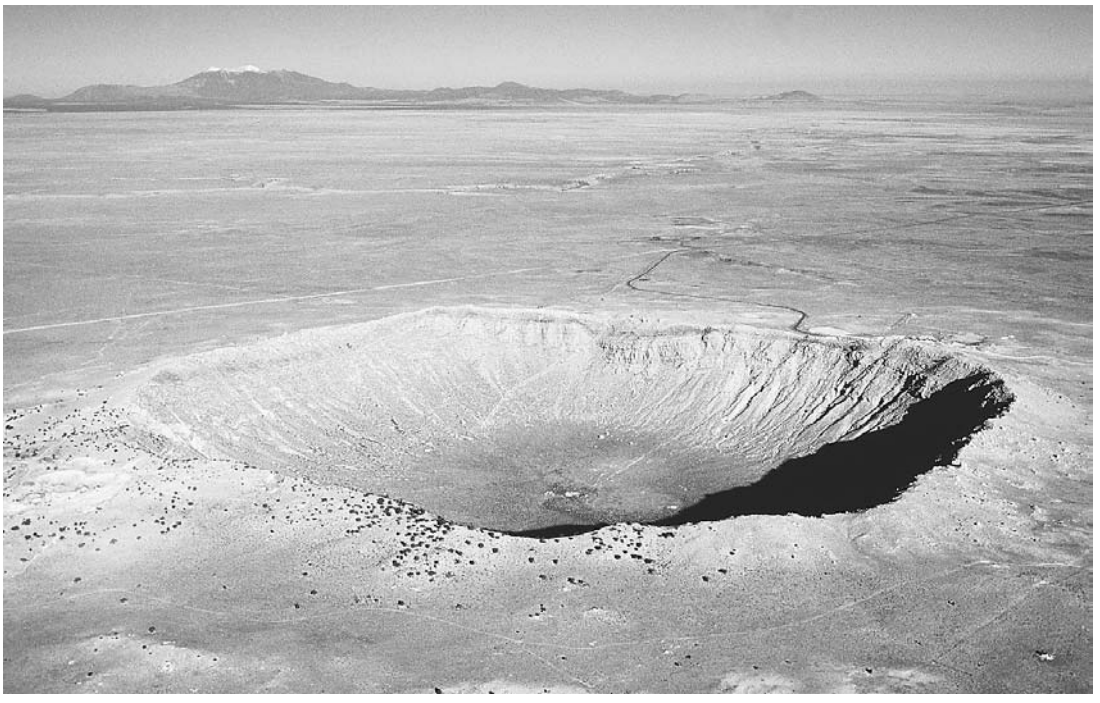
Uniformitarianism

Late in the eighteenth century, the Scottish geologist James Hutton (1726–1797) put forward an idea that transcended the debate over Earth's origins. Rather than speculate as to how Earth had come into being, Hutton analyzed the processes at work on the planet in his time and reasoned that they must be a key to understanding the means by which Earth was shaped. This was the principle of uniformitarianism, which is still a key concept in the study of Earth. Thanks to his introduction of this influential idea, Hutton today is regarded as the father of modern scientific geology.

Uniformitarianism, in general, is the idea that the geologic processes at work today provide a key to understanding the geologic past. This means that the laws of nature have always been the same. The uniformitarianism promoted by Hutton and his fellow Scottish geologist Charles Lyell (1797–1875), however, has undergone some modification, namely, by the addition of the qualifying statement that the speed and intensity of those processes may not always be the same at any juncture in geologic history. For instance, land does not erode today at the same rate that it did before plants existed to hold rocks and soil in place.

GOULD'S FOUR UNIFORMITIES. In the late twentieth century, the American paleontologist Stephen Jay Gould (1941–2002) identified four different meanings of uniformity in science, not all of which are equally valid. Gould's listing and analysis of these four meanings is as follows:

- Uniformity of law: The assumption that natural laws do not change over time. This idea governs all sciences.
- Uniformity of process: The idea embodied in the most well-known definition of geo-



Meteor Crater, Arizona. Most notable among catastrophe theories of Earth's formation is the collision of meteorites. *(© Francois Gohier/Photo Researchers. Reproduced by permission.)*

logic uniformitarianism, "The present is key to the past."

- Uniformity of rate: The incorrect assumption that the rate at which processes occur presently is the same as the rate at which they occurred in the past.
- Uniformity of state: The incorrect assumption that the state of the universe always has been as it is today.

As noted, uniformity of law is essential to all sciences. For instance, there is every reason to believe that the conservation of energy (a law stating that the total amount of energy in the universe remains constant) always has been the case. If the contrary were true, the conservation of energy could no longer properly be called a law, because it might cease to be the case at some time in the future.

The statement "The present is key to the past" was formulated by yet another Scottish geologist, Sir Archibald Geikie (1835–1924). Geikie's statement often has been criticized as an oversimplification, because processes that occurred in the past may not necessarily be occurring now, or vice versa, even though they could occur again. This idea has required modification of uniformitarianism, as noted earlier, to take into account the fact that the speed and intensity of processes may not always be the same. Part of this modification has involved acceptance of a form of catastrophism, discussed later in this essay.

Variations in the speed and intensity of processes also were addressed by Gould, with his observation that "uniformity of rate" is a fallacy. So, too, is "uniformity of state," which is one of the few areas on which adherents of creationism (a strict interpretation of the Genesis account) would agree with their opponents. Even the Bible, after all, says "In the beginning ... the earth was without form, and void."

Catastrophism

In *Theory of the Earth* (1795), Hutton suggested that the weathering effects of water produced the sedimentary layers of Earth. Based on observation of river flow and mud content, he realized that this process would require much longer than 6,000 years. So, too, did Lyell, author of the highly influential *Principles of Geology,* which appeared in 12 editions from 1830 to 1875 and which presented a strict version of uniformitarianism.

Aqueducts and other structures erected by the Romans had stood for a good one-fourth to

one-third of the entire history of Earth, assuming that it was as young as Ussher's biblical interpretation implied. Yet these Roman constructions had experienced very little weathering and certainly much less than mountains would have had to experience to leave behind the sediments observed by geologists. Surely, then, Earth must be millions upon millions of years old, not just a few thousand.

Cuvier's catastrophic theory. Not so, countered adherents of a movement known as catastrophism, which arose in opposition to uniformitarianism during the late eighteenth and early nineteenth centuries. Catastrophism associates geologic phenomena with sudden, dramatic changes rather than ongoing and long-term processes, as in uniformitarianism. The leading proponent of catastrophism was the French geologist Baron Georges Cuvier (1769–1832), who used this theory to explain unconformities. These apparent gaps in the geologic record, revealed by observing rock layers, or strata, are discussed in the essay, Stratigraphy.

Whereas Cuvier's countryman (and fellow French noble) Buffon had asserted that Earth was 75,000 years old while actually believing that it was much older, Cuvier maintained that the planet is *just* 75,000 years old. The formation of mountains and other landforms, which should have taken millions of years, could be explained by sudden, violent changes, an example of which was Noah's Flood in the Book of Genesis. As the ocean waters receded, they moved rocks far from their sources, carved out valleys, and left behind lakes and other bodies of fresh water.

Catastrophism today. As more and more evidence for a very old Earth began to accumulate during the nineteenth century, catastrophism fell into disfavor. Discoveries from the 1970s onward, however, influenced a new look at catastrophism, and, as a result, the idea has received new attention in later years.

This has not led to a wholesale endorsement of creationism; rather, scientists have come to understand that the generally steady pace of processes on Earth periodically is broken by catastrophic events. Most notable among types of catastrophe is the collision of a meteorite with Earth, a remarkable example of which apparently occurred some 65 million years ago. That dramatic event seems to have forced so much dust and gas into the atmosphere that it blocked out the Sun, leading to the ultimate extinction of the dinosaurs.

Understanding Geologic Time

So just how old *is* Earth? Modern earth scientists working in the realm of historical geology, and specifically geochronology, estimate its age at about 4.6 billion years. (The dating techniques used to determine the age of the planet are discussed in the essay Stratigraphy.) Such a vast span of time is more than a little difficult for humans to comprehend, given the fact that our lives last 70–80 years, on average, and the entire history of human civilization is only about 5,500 years long.

For this reason, it is helpful to use scales of comparison, such as that offered at the Web site listed under the title *Comprehending Geologic Time.* Suppose that the entire geologic history of Earth were likened to a single year of 365.25 days, starting with the formation of the planet from a cloud of dust and ending with the present. More than two months would have been required simply for the accretion of Earth from a gas cloud to a planetesimal to something like its present form, but by about March 5 this evolution would have been accomplished.

The entire spring would be analogous to a long, long period of time in which Earth was pounded by meteor showers and the oceans began to form. Not even the oldest known rocks date back this far, and many of our ideas about this phase in Earth's history are based on conjecture. Much more is known about the second half of geologic history, beginning with the origins of the first single-cell life-forms on June 16.

From single cells to dinosaurs. We are now almost halfway through the year and still a long, long way from any sort of complex living beings. This is not surprising, given the fact that the formation of the continental plates and the development of oxygen in the atmosphere would have occurred only by about August 26. Even in the week after Thanksgiving, the most complex organisms would have been snails. Finally, a few days before the beginning of December, creatures would have begun to invade the land.

We tend to associate the dinosaurs with the early phases of Earth's history, but this only illustrates our distorted view of geologic time. In fact the Jurassic period, when dinosaurs roamed

KEY TERMS

CATASTROPHISM: The idea that geologic phenomena are brought about by sudden dramatic changes rather than ongoing and long-term processes, as in uniformitarianism. Although it was once used to promote the idea of a very young Earth, catastrophism today is accepted, in a very modified form, by many earth scientists.

GEOCHRONOLOGY: The study of Earth's age and the dating of specific formations in terms of geologic time.

GEOLOGY: The study of the solid earth, in particular, its rocks, minerals, fossils, and land formations.

GEOMYTHOLOGY: Folklore inspired by geologic phenomena.

HISTORICAL GEOLOGY: The study of Earth's physical history. Historical geology is one of two principal branches of geology, the other being physical geology.

QUALITATIVE: Involving a comparison between qualities that are not defined precisely, such as "fast" and "slow" or "warm" and "cold."

QUANTITATIVE: Involving a comparison between precise quantities—for instance, 10 lb. versus 100 lb. or 50 mi. per hour versus 120 mi. per hour.

SCIENTIFIC METHOD: A set of principles and procedures for systematic study that includes observation; the formation of hypotheses, theories, and laws; and continual testing and reexamination.

SEDIMENT: Material deposited at or near Earth's surface from a number of sources, most notably preexisting rock.

STRATIGRAPHY: The study of rock layers, or strata, beneath Earth's surface.

UNCONFORMITY: An apparent gap in the geologic record, as revealed by observing rock layers, or strata.

UNIFORMITARIANISM: The idea that the geologic processes at work today provide a key to understanding the geologic past. The speed and intensity of those processes, however, may not always be the same at any juncture in geologic history. Uniformitarianism usually is contrasted with catastrophism.

WEATHERING: The breakdown of rocks and minerals at or near the surface of Earth due to physical or chemical processes or both.

Earth, would be parallel to a period of about five days, from December 15 to 20. By Christmas Day, the meteorite referred to earlier would have hit Earth, and the dinosaurs would be headed toward extinction, their dead bodies eventually forming the fossil fuels that have powered much of human civilization.

THE SHORT SPAN OF HUMANITY'S EXISTENCE. By this point, we are within a few days of the year's end, and yet nothing remotely resembling a human has appeared. Our own species, *Homo sapiens,* would not have come on the scene until the last 0.16 days of the year—that is, at a few minutes after 8:00 p.m. on December 31. The New Year's Eve countdown would be nearing by the time human civilization began, at about 42 seconds before midnight.

Now we have come to a period about 6,000 years ago, or the point at which, according to Bishop Ussher, Earth was created. No wonder many people wanted to believe in a young Earth, and some even hold on to that belief today: when viewed against the backdrop of the planet's true age, humanity seems very insignificant indeed.

Christ's birth would have occurred at about 14 seconds before midnight, and the final 10-second countdown would begin about the time the Roman Empire fell. The life span of the average person would correspond to about half a second or less.

How Do We Know Earth's Age?

What we know about Earth's age comes, of course, not from direct observation but from the study of materials. One of the most important techniques for determining the age of samples taken from the earth is radiometric dating, discussed in more detail in Geologic Time. Radiometric dating involves ratios between two different kinds of atoms for a given element: stable and radioactive isotopes. Because chemists know how long it takes for half the isotopes in a given sample to stabilize (a half-life), they can judge the age of the sample by examining the ratio of stable to radioactive isotopes. In the case of uranium, one isotopic form, uranium-238, has a half-life of 4,470 million years, which is very close to the age of Earth itself. Use of uranium dating has detected rocks of an age between 3.8 and 3.9 billion years old, as well as even older crystal formations that suggest the earth had solid ground as early as 4.2 billion years ago.

A rock discovered in the Australian desert during the early 1980s appears to be the oldest rock sample in the world, according to data originally reported in *Nature* and included on the *Scientific American* Web site in early 2001. This zircon crystal, according to Simon Wilde of Curtin University in Western Australia, is 4.4 billion years old. Wilde and associates reported that extensive study of the sample suggested that at the time of its formation, Earth was already covered in water—something that had supposedly happened many millions of years later. If this was the case, it could suggest the possibility that life appeared much earlier than has previously been supposed, and perhaps even that life disappeared and reappeared several times before finally taking hold.

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GEOLOGIC TIME

CONCEPT

The expression geologic time refers to the vast span from Earth's beginnings to the present, about 4.6 billion years. To examine the history of Earth, one must discard most familiar ideas about time. Instead of thinking in terms of years, centuries, or even millennia, the most basic unit is a million years, and even that is rather small when compared with the four eons into which geologic time is divided. Earth scientists' knowledge of the first three eons is fairly limited. What they do know comes from a combination of absolute dating, mostly by the study of radioactive decay, and relative dating through the stratigraphic record of rock layers.

HOW IT WORKS

Historical Geology

The study of geologic time is encompassed within the larger subject of historical geology. The latter, the study of Earth's physical history, is one of the two principal branches of geology, the other being physical geology, or the study of Earth's physical components and the forces that have shaped them.

The background of historical geology is discussed in some detail within the Historical Geology essay. Its principal subdisciplines include stratigraphy, the study of rock layers, or strata, beneath Earth's surface; geochronology, the study of Earth's age and the dating of specific formations in terms of geologic time; sedimentology, the study and interpretation of sediments, including sedimentary processes and formations; paleontology, the study of fossilized plants and animals; and paleoecology, the study of the relationship between prehistoric plants and animals and their environments. Several of these subjects are examined in essays within this book.

Divisions of Geologic Time

Geologic time is divided according to two scales. The more well-known of these is the geologic scale, which divides time into named groupings according to six basic units: eon, era, period, epoch, age, and chron. In addition, the chronostratigraphic scale identifies successive layers of rock with specific units of time.

As noted earlier, stratigraphy is the study of rock layers, or strata, beneath Earth's surface, while chronostratigraphy is a subdiscipline devoted to studying the ages of rocks and what they reveal about geologic time. The chronostratigraphic scale likewise has six time units, analogous to those of the geologic scale: eonothem, erathem, system, series, stage, and chronozone. For the most part, we will not be concerned with the chronostratigraphic terms in the present context.

RELATIVE AND ABSOLUTE TIME. To discuss the divisions of geologic time, it is necessary first to discuss the concepts of relative and absolute time. The term *relative* refers to a quality or quantity that is comparative, or dependent on something else. Its opposite is *absolute,* a term designating a quality or quantity that is independent and not defined in relation to another quality or quantity.

If we say that Abraham Lincoln was born in 1809, it is an absolute designation of his birth year, whereas if we say that he was born 10 years after the death of George Washington (which



Subatomic particle tracks. Study of radioactive decay, or the release of subatomic particles, is a method of absolute dating. *(© John Giannicchi/Photo Researchers. Reproduced by permission.)*

occurred in 1799), that is an example of a relative time measurement. In actuality, of course, there is no truly absolute measure of time. For example, the reference to 1809 as Lincoln's birth year is based on the system of time measurement developed in the West, which, in turn, is based on early ideas regarding the date of Christ's birth. (As it turns out, Christ likely was born in about 6 B.C.)

Since the B.C./A.D. system of dating is widely accepted and used, or at least recognized, by most of the non-Western world, a date rendered according to this system constitutes the closest possible approximation to an absolute measure of time. In any case, one knows the difference between absolute and relative when one sees it: thus, to say that Lincoln was born ten years after Washington died is obviously and unmistakably a relative statement.

In terms of geology, the absolute age of a geologic phenomenon is its age in Earth years. On the other hand, its relative age is its age in comparison with other geologic phenomena, particularly the stratigraphic record of rock layers. Thus, references to relative age are given in terms of chronostratigraphic time divisions rather than millions of years.

Relative Dating

Given the meaning of relative age, it is easy enough to guess what relative dating would be, once one knows that dating, in a scientific context, usually refers to any effort directed toward finding the age of a particular item or phenomenon. Relative dating, then, assigns an age relative to that of other items, whereas absolute dating determines the age in actual years or millions of years.

One of the principal means of relative dating is through stratigraphy, which is based on the assumption that the deeper a layer of rock lies beneath Earth's surface, the earlier it was deposited. This holds true, however, for only one of the three major types of rock: sedimentary rock, which is formed by compression and deposition (i.e., formation of deposits) on the part of rock and mineral particles. (The other types of rock are igneous and metamorphic.)

Aside from stratigraphy, discussed in a separate essay, other relative dating techniques include seriation, faunal dating, and pollen dating, or palynology. Used, for instance, in archaeological studies, seriation analyzes the abundance of a particular item (for instance, pieces of pottery) and assigns relative dates based on this abundance. The term faunal dating refers to fauna, or animal life, and faunal dating is the use of animal bones to determine age. Finally, pollen dating, or palynology, involves analysis of pollen deposits.

Absolute Dating

As dating technology has progressed, it has become increasingly possible for scientists to provide absolute dates for specimens. One such method, introduced in the 1960s, is amino-acid racimization. Amino acids exist in two forms, designated *L*-forms and *D*-forms, which are stereoisomers, or mirror images of each other. Virtually all living organisms (except some microbes) incorporate only the L-forms, but once the organism dies the L-amino acids gradually convert to D-amino acids. Several factors influence the rate of conversion, and though amino-acid racimization was popular in the 1970s, these uncertainties have led scientists to treat it with increasing disfavor.

The principles that undergird amino-acid racimization, however, are essential to most forms of absolute dating. Generally, absolute dating uses ratios between the quantities of a particular substance (let us call it *Substance A*) and the quantities of a mirror substance (*Substance B*) to which it is converted over a period of time. The greater the ratio of Substance B to Substance A, the longer the time that has elapsed. The scale of time for various substances, however, differs greatly. Carbon-14 decay, for instance, takes place over a few thousand years, making it useful for measuring the age of human artifacts. On the other hand, uranium decay takes billions of years, and thus it is used for dating rocks.

Cation-ratio dating, for instance, measures the amount of cations, or positively charged ions, that have formed on an exposed rock surface. (An ion is an atom or group of atoms that have lost or gained electrons, thus acquiring a net electric charge. Electron loss creates a cation, as opposed to a negatively charged anion, created when an atom or atoms gain electrons.) Cation-ratio dating is based on the idea that the ratio of potassium and calcium cations to titanium cations decreases with age. It is applicable only to rocks in desert areas, where the dry air stabilizes the cation "varnish."

RADIOACTIVE DECAY. Various forms of radiometric dating employ ratios as well. Every element has a particular number of protons, or positively charged particles, in its nucleus, but it may have varying numbers of neutrons, particles with a neutral electric charge but relatively great mass. (Neutrons and protons have approximately the same mass, which is more than 1,800 times greater than that of an electron.) When two or more atoms of the same element have a differing number of neutrons, they are called isotopes.

Some types of isotopes "fit" better with a particular element and tend to be most abundant. For instance, carbon has six protons, and it so happens that the most abundant carbon isotope has six neutrons. Because there are six protons and six neutrons, totaling 12, this carbon isotope is designated *carbon-12,* which accounts for 98.9% of the carbon in nature. Generally speaking, the most abundant isotope is also the most stable one, or the one least likely to release particles and thus change into something else.

This release of particles is known as radioactive decay. In the context of radioactivity, "to decay" does not mean "to rot" rather, the isotope expels alpha particles (positively charged helium nuclei), beta particles (either electrons or subatomic particles called positrons), or gamma rays, which occupy the highest energy level in the electromagnetic spectrum. In so doing, it eventually will become another isotope, either of the same element or of a different element, and will stabilize. The amount of time it takes for half the isotopes in a sample to stabilize is called its half-life. This half-life varies greatly between isotopes, some of which have a half-life that runs into the billions of years.

Determining Absolute Age

When an organism is alive, it incorporates a certain ratio of carbon-12 in proportion to the amount of the radioisotope (that is, radioactive isotope) carbon-14 that it receives from the atmosphere. As soon as the organism dies, however, it stops incorporating new carbon, and the ratio between carbon-12 and carbon-14 will begin to change as the carbon-14 decays to form nitrogen-14. A scientist can use the ratios of carbon-12, carbon-14, and nitrogen-14 to ascertain the age of an organic sample.

Carbon-14, known as radiocarbon, has a half-life of 5,730 years, meaning that it takes that long for half the isotopes in a sample to decay to nitrogen-14. Note that half-life is *not* half the amount of time it takes for the entire sample to decay, especially because the first half of the sample usually decays faster than the second half. Imagine, for instance, that you had 100 units and wanted to reduce it to zero units by continually halving it. At first, the results would be dramatic, as 100 became 50, then 25, then 12.5, and so on. Eventually you would be down to smaller and smaller fractions of 1, and each division by 2 would yield a smaller number—but never zero.

Radioactive decay works that way as well, and, thus, while carbon-14 has a half-life of less than 6,000 years, it takes much longer than 6,000 years for the other half of the isotopes in a carbon-14 sample to decay. For this reason, the use of proper instrumentation makes it possible to judge the age of charcoal, wood, and other biological materials over a span of as long as 70,000 years. While this may be useful for archaeologists, it is not very helpful for measuring the vast spans

of time encompassed in the earth sciences. Furthermore, there is a good likelihood that the sample will become contaminated by additional carbon from the soil. Moreover, it cannot be said with certainty that the ratio of carbon-12 to carbon-14 in the atmosphere has been constant throughout time.

POTASSIUM-ARGON DATING. Much more useful, from the standpoint of geology, is potassium-argon dating. When volcanic rocks are subjected to extremely high temperatures, they release the element argon, a noble gas. As the rocks cool, the stable isotope argon-40 accumulates. Because argon-40 is formed by the radioactive decay of a potassium isotope, potassium-40, the amount of argon-40 that forms is proportional to the rate of decay for potassium-40.

Potassium-40 has a half-life of 1.3 billion years, and with the help of argon-40, geologists have been able to estimate the age of volcanic layers above and below fossil and artifact remains in eastern Africa. Potassium-argon dating is most effective for rocks that are at least three million years old, because it takes about that long to accumulate enough argon-40 to make accurate measurements possible.

This brings up a notable aspect of radiometric dating techniques. No one technique is most effective; rather, each technique is suited to a particular span of time. Thus, potassium-argon dating would be virtually useless for measuring the relatively short time scales for which radiocarbon dating is ideally suited. The converse is also true: as we have noted, radiocarbon dating simply does not cover a wide enough span of time to be useful in most geologic studies.

URANIUM-SERIES DATING. We now come to the element most useful for dating the age of material samples over a broad chronological spectrum: uranium, which has an atomic number of 92. This means that it has 92 protons in its nucleus, making uranium atoms typically the heaviest atoms that occur in nature. (There are about 20 elements with atomic numbers higher than 92, but all of them have been created artificially, either in laboratories or as the result of nuclear testing.)

Both uranium and thorium, with an atomic number of 90, have unstable "parent" isotopes that decay into even more unstable "daughter" isotopes before eventually stabilizing as isotopes of lead. These daughter isotopes have half-lives that range from just a few years to a few hundred thousand years, whereas the half-lives of the parent isotopes are much longer. That of uranium-235, for instance, is 7.038×10^8 years, or more than 700 million years. On the other hand, the daughter isotope protactinium-231 has a half-life of 32,760 years.

When uranium-235 is deposited in an area, over time it will decay to form daughter isotopes. Assuming that the sample has been left undisturbed (isotopes have neither entered nor exited the deposit since its initial formation), the age of certain types of sample may thus be determined. For mollusks and corals, for instance, the amount of protactinium-231, a daughter isotope that begins to accumulate only after the organism dies, makes it possible to date a sample. In some cases, large amounts of a daughter isotope may be deposited initially alongside samples of a parent, and if these are present in water, the quantities of each can be judged according to the amount that has dissolved. For example, the daughter isotope uranium-234 dissolves more readily in water than the parent, uranium-238.

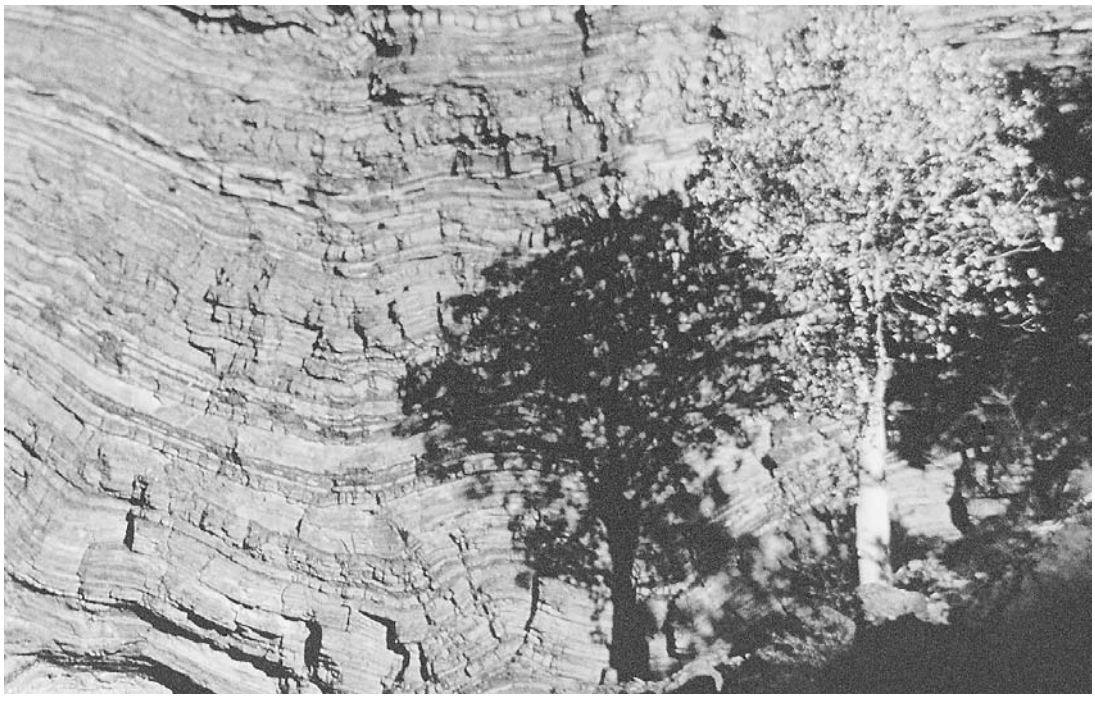
REAL-LIFE APPLICATIONS

How Do We Know Earth's Age?

We can now begin to answer a question almost inevitably raised when discussing geologic time: just how do we know that Earth is about 4.6 billion years old? A clue lies in the half-life of uranium-238, which is 4.47×10^9 years, or 4,470 million years. Geologists typically would abbreviate this as 4.47 Ga, the latter referring to "gigayears," a unit of a billion years.

As uranium atoms undergo fission, or splitting, this process releases energy that causes marks, called tracks, to form on the surface of volcanic minerals. In splitting, two daughter atoms shoot away from each other, forming tracks, and thus the rate of track formation is proportional to the rate of decay on the part of the parent isotope.

Incidentally, fission-track dating with uranium-238 defies the statement made earlier that certain types of dating are more suited to long periods of time, while others are best for shorter periods. When heated, the tracks disappear from



Relative dating uses the stratigraphic record of rock layers, as seen in the wall of this gorge, to determine the age of a geologic formation compared with others. *(© B. Bachman/Photo Researchers. Reproduced by permission.)*

a sample containing uranium-238, thus resetting the dating clock. As a result, if an object was heated just a few decades ago, it can be dated; so, too, can meteorites billions of years old.

Most meteorites found in the solar system tend to be about 4.56 Ga; hence, the rough figure of 4.6 Ga is used for the point at which the solar system, including Earth, began to form. The oldest known materials on Earth are zircon crystals from western Australia, dated about 4.3 Ga. Small samples of gneiss in Canada's Northwest Territories have been dated to about 4.0 Ga, but the oldest large-scale sample is a belt of 3.8 Ga gneiss in western Greenland.

A Question of Scale

Having discussed at least the rudiments of the dating system used by geologists, it is possible to examine geologic time itself. This requires a mental adjustment of monumental proportions, because one must discard all notions used in studying the history of human civilization. Concepts such as medieval, ancient, and prehistoric are practically useless when discussing geologic time, which dwarfs the scale of human events.

Human civilization has existed for about 5,500 years, the blink of an eye in geologic terms. Even the span of time that the human species, *Homo sapiens,* has existed—about two million years—is negligible in the grand scheme of Earth's history. The latter stretches back some 4,600 million years, meaning that human beings have existed on this Earth for just 0.043% of the planet's history. As discussed in the essay Historical Geology, if the entire history of Earth were likened to a single year, humans would have appeared on the scene at a few minutes after 8:00 p.m. on December 31. Human civilization would date only from about 42 seconds before midnight, and the age of machinery and industrialization would not fill up even the final two seconds of the year.

Another analogy: Los Angeles to New York. When discussing distances in space, astronomers dispense with miles, because they would be useless, given the vastness of the scale involved. The same is true of geologic time, in which the concept of years is hardly relevant. Instead, geologists speak in terms of millions of years, or megayears, abbreviated "Ma." (Geologists also use the much larger unit of a gigayear, to which we have already

referred.) To discuss the age of Earth in terms of years, in fact, would be rather like measuring the distance from Los Angeles to New York in feet; instead, of course, we use miles. Now let us consider geologic time in terms of the 2,462 mi. between Los Angeles and New York, with 1 mi. equal to 1.8684 Ma, or 1,868,400 years.

Suppose we have left Los Angeles and driven a good deal of the distance to New York—46% of the way, in fact, to western Nebraska, a spot analogous to the beginning of the Proterozoic era. In the preceding miles, a duration equivalent to about 1,133 Ma, Earth was formed from a cloud of gas, pounded by meteors, and gradually became the home to oceans—but no atmosphere resembling the one we know now. The end of the Proterozoic era (about 545 Ma, or 545 million years ago) would be at about 88% of the distance from Los Angeles to New York—somewhere around Pittsburgh, Pennsylvania. By this point, the continental plates have been formed, oxygen has entered the atmosphere, and soft-bodied organisms have appeared.

We are a long way from Los Angeles, and yet almost the entire history of life on Earth, at least in terms of relatively complex organisms, lies ahead of us. If we skip ahead by about 339 Ma (a huge leap in terms of biological development), we come to the time when the dinosaurs appeared. We are now 95% of the way from the beginning of Earth's history to the present, and if measured against the distance from Los Angeles to New York, this would put us at a longitude equivalent to that of Baltimore, Maryland. Another 89 mi. would put us at about 65 million years ago, or the point when the dinosaurs became extinct.

We would then have only 33.7 mi. to drive to reach the point where humans appeared, by which time we would be in the middle of Manhattan. Compared with the distance from Los Angeles to New York, the span of human existence would be much smaller than the cab ride from Central Park to the Empire State Building. The entire sweep of written human history, from about a thousand years before the building of the pyramids to the beginning of the third millennium A.D., would be much smaller than a city block. In fact, it would be about the width of a modest storefront, or 15.54 ft.

The Very, Very Distant Past

So what happened for all those hundreds of millions of years before humans appeared on the scene? We will attempt to answer that question in an extremely cursory, abbreviated fashion, but for further clarification, the reader is strongly encouraged to consult a chart of geologic time. Such a chart can be found in virtually any earth sciences textbook; indeed, several versions (including a chronostratigraphic chart) may appear in a single book.

In addition to showing geologic time in both absolute and relative terms, these charts typically provide information about the magnetic polarity over a given span, since that has changed many times since Earth came into existence. In other words, what is today the magnetic North Pole was once the magnetic South Pole, and vice versa. (For more on this subject, see the discussion of paleomagnetism in the entries Plate Tectonics and Geomagnetism.)

As one might expect, disagreement between earth scientists is greatest with regard to the most distant phases of Earth's geologic history. This encompasses nearly 90% of all geologic time, dating back to about 545 Ma, thus showing how little geologists know, even today, about the geologic events of the very distant past. For this reason, when discussing Precambrian time, it is usually necessary to consider only the three eons that composed it. Discussion of era and period, on the other hand, is reserved for the three eras, and 11 periods, of the Phanerozoic eon. The smaller division of epoch is generally only of concern with regard to the most recent era, the Cenozoic. As for divisions smaller than an epoch, these will not concern us here.

THE PRECAMBRIAN EONS. The last paragraph of the preceding section encompasses a number of ideas, which now need to be explained, in at least general terms. The term *Precambrian* encompasses about four billion years of Earth's history, including three of the four eons (Hadean or Priscoan, Archaean, and Proterozoic) of the planet's existence. The names of these eons are derived from Greek, with the first being taken from the name of the deity who ruled over the Underworld. The latter two are derived, respectively, from the Greek words for *beginning* and *new life.*

The Hadean eon (sometimes called the Priscoan) lasted from about 4,560 Ma to 4,000

Ma ago, when the planet was being formed, or accreted, as pieces of solid matter floating around in the young solar system began to join one another. Meteorites showered the planet, bringing both solid matter and water, and thus forming the basis of the oceans. There was no atmosphere as such, but by the end of the eon, volcanic activity had ejected enough carbon dioxide and other substances into the air to form the beginnings of one. The oceans began to cool, making possible the beginnings of life—that is, molecules of carbon-based matter that were capable of replicating themselves. These appeared at the end of the Hadean eon, perhaps arriving from space in a meteorite.

The boundaries of the Precambrian eons are far from certain, so it is possible only to say that the Archaean eon lasted from about 4,000 Ma to 2,500 Ma ago. The earliest known datable materials, described earlier, all come from this time; in fact, outcrops of Archaean rock have been found on all seven continents. The rocks of this eon contain the first clear evidence of life, in the form of microorganisms. Over the course of the Archaean eon, prokaryotes, or cells without a nucleus, made their appearance, and later they were followed by eukaryotes, or cells with a nucleus.

During this great span of time, more than 20% of Earth's history, the atmosphere and hydrosphere developed considerably, even as the biosphere had its true beginnings. As for the geosphere, it also matured enormously in the course of the Archaean eon. During the Hadean eon, Earth's interior had begun to differentiate into core, mantle, and crust, and cooling in the two upper layers influenced the beginnings of the earliest plate-tectonic activity (see Plate Tectonics).

Even longer was the Proterozoic eon, which appears to have lasted from about 2,500 Ma to 545 Ma. This phase saw the beginnings of very basic forms of plant life, such that photosynthesis (the biological conversion of electromagnetic energy from the Sun into chemical energy in plants) began to take place. Plate-tectonic processes accelerated as well, with continents moving about over Earth's surface and smashing against one another. Oxygen in the atmosphere assumed about 4% of its present levels, but animal life still consisted primarily of eukaryotes.

THE PHANEROZOIC ERAS AND PERIODS. The end of the Proterozoic eon, once again, is not sharply defined in the stratigraphic record, such that there is considerable dispute as to the time periods involved. In any case, it is clear that the pace of development in the biosphere increased dramatically in the Phanerozoic, the eon in which we are now living. During the beginning of the Phanerozoic eon, algae appeared, and there followed an acceleration in the development of living organisms that ultimately produced the varied biosphere we know today.

As noted earlier, the only eras and periods that need concern most students of the earth sciences are those of the Phanerozoic eon. The three eras are as follows:

Eras of the Phanerozoic Eon

- Paleozoic (about 545 to 248.2 Ma)
- Mesozoic (about 248.2 to 65 Ma)
- Cenozoic (about 65 Ma to the present)

Within these eras are the following periods:

Periods of the Paleozoic Era

- Cambrian (about 545 to 495 Ma)
- Ordovician (about 495 to 443 Ma)
- Silurian (about 443 to 417 Ma)
- Devonian (about 417 to 354 Ma)
- Carboniferous (about 354 to 290 Ma)
- Permian (about 290 to 248.2 Ma)

Periods of the Mesozoic Era

- Triassic (about 248.2 to 205.7 Ma)
- Jurassic (about 205.7 to 142 Ma)
- Cretaceous (about 142 to 65 Ma)

Periods of the Cenozoic Era

- Palaeogene (about 65 to 23.8 Ma)
- Neogene (about 23.8 to 1.8 Ma)
- Quaternary (about 1.8 Ma to present)

These divisions, as well as the two most recent epochs of the Quaternary period (Pleistocene and Holocene), are discussed elsewhere in this book. It should be noted that there are variations for many of the eon, era, and period names given here; also, the Palaeogene and Neogene are often grouped together as a subera called the Tertiary. The latter nomenclature fits with a mnemonic device used by geology students memorizing the names of the 11 Phanerozoic periods: "Camels Ordinarily Sit Down Carefully; Perhaps Their Joints Creak Tremendously Quietly."

KEY TERMS

ABSOLUTE AGE: The absolute age of a geologic phenomenon is its age in Earth years. Compare with *relative age.*

ATMOSPHERE: In general, an atmosphere is a blanket of gases surrounding a planet. Unless otherwise identified, however, the term refers to the atmosphere of Earth, which consists of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon, which together comprise 0.07%.

ATOM: The smallest particle of an element, consisting of protons, neutrons, and electrons. An atom can exist either alone or in combination with other atoms in a molecule.

BIOSPHERE: A combination of all living things on Earth—plants, animals, birds, marine life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

CHRONOSTRATIGRAPHY: A subdiscipline of stratigraphy devoted to studying the ages of rocks and what they reveal about geologic time.

DATING: Any effort directed toward finding the age of a particular item or phenomenon. Methods of geologic dating are either relative (i.e., comparative and usually based on rock strata) or absolute. The latter, based on such methods as the study of radioactive isotopes, usually is given in terms of actual years or millions of years.

ELECTRON: A negatively charged particle in an atom, which spins around the nucleus.

ELEMENT: A substance made up of only one kind of atom. Unlike compounds, elements cannot be chemically broken into other substances.

EON: The longest phase of geologic time. Earth's history has consisted of four eons, the Hadean or Priscoan, Archaean, Proterozoic, and Phanerozoic. The next-smallest subdivision of geologic time is the era.

EPOCH: The fourth-longest phase of geologic time, shorter than an era and longer than an age and a chron. The current epoch is the Holocene, which began about 0.01 Ma (10,000 years) ago.

ERA: The second-longest phase of geologic time, after an eon. The current eon, the Phanerozoic, has had three eras, the Paleozoic, Mesozoic, and Cenozoic, which is the current era. The next-smallest subdivision of geologic time is the period.

GA: An abbreviation meaning "gigayears," or "billion years." The age of Earth is about 4.6 Ga.

GEOCHRONOLOGY: The study of Earth's age and the dating of specific formations in terms of geologic time.

GEOLOGIC TIME: The vast stretch of time over which Earth's geologic development has occurred. This span (about 4.6 billion years) dwarfs the history of human existence, which is only about two million years. Much smaller still is the span of human civilization, only about 5,500 years.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live

KEY TERMS CONTINUED

and which provides them with most of their food and natural resources.

HISTORICAL GEOLOGY: The study of Earth's physical history. Historical geology is one of two principal branches of geology, the other being physical geology.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

ISOTOPES: Atoms that have an equal number of protons and hence are of the same element but differ in their number of neutrons. This results in a difference of mass. An isotope may be either stable or radioactive.

MA: An abbreviation used by earth scientists, meaning "million years" or "megayears." When an event is dated to, for instance, 160 Ma, it usually means that it took place 160 million years ago.

NEUTRON: A subatomic particle that has no electric charge. Neutrons are found at the nucleus of an atom, alongside protons.

NUCLEUS: The center of an atom, a region where protons and neutrons are located and around which electrons spin.

PERIOD: The third-longest phase of geologic time, after an era. The current eon, the Phanerozoic, has had 11 periods, and the current era, the Cenozoic, has consisted of three periods, of which the most recent is the Quaternary. The next-smallest subdivision of geologic time is the epoch.

PRECAMBRIAN TIME: A term that refers to the first three of four eons in Earth's history, which lasted from about 4,Ma to about 545 Ma ago.

PROTON: A positively charged particle in an atom.

RADIOACTIVITY: A term describing a phenomenon whereby certain materials are subject to a form of decay brought about by the emission of high-energy particles or radiation. Forms of particles or energy include alpha particles (positively charged helium nuclei), beta particles (either electrons or subatomic particles called *positrons*, or gamma rays, which occupy the highest energy level in the electromagnetic spectrum.

RADIOMETRIC DATING: A method of absolute dating using ratios between "parent" isotopes and "daughter" isotopes, which are formed by the radioactive decay of parent isotopes.

RELATIVE AGE: The relative age of a geologic phenomenon is its age in comparison with other geologic phenomena, particularly the stratigraphic record of rock layers. Compare with *absolute age.*

SEDIMENT: Material deposited at or near Earth's surface from a number of sources, most notably preexisting rock.

SEDIMENTARY ROCK: Rock formed by compression and deposition (i.e., formation of deposits) on the part of other rock and mineral particles.

SEDIMENTOLOGY: The study and interpretation of sediments, including sedimentary processes and formations.

STRATIGRAPHY: The study of rock layers, or strata, beneath Earth's surface.

WHERE TO LEARN MORE

Boggy's Links to Stratigraphy and Geochronology (Web site). <http://geologylinks.freeyellow.com/stratigraphy.html>.

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STRATIGRAPHY

CONCEPT

Stratigraphy is the study of rock layers (strata) deposited in the earth. It is one of the most challenging of geologic subdisciplines, comparable to an exacting form of detective work, yet it is also one of the most important branches of study in the geologic sciences. Earth's history, quite literally, is written on the strata of its rocks, and from observing these layers, geologists have been able to form an idea of the various phases in that long history. Naturally, information is more readily discernible about the more recent phases, though even in studying these phases, it is possible to be misled by gaps in the rock record, known as unconformities.

HOW IT WORKS

The Foundations of Stratigraphy

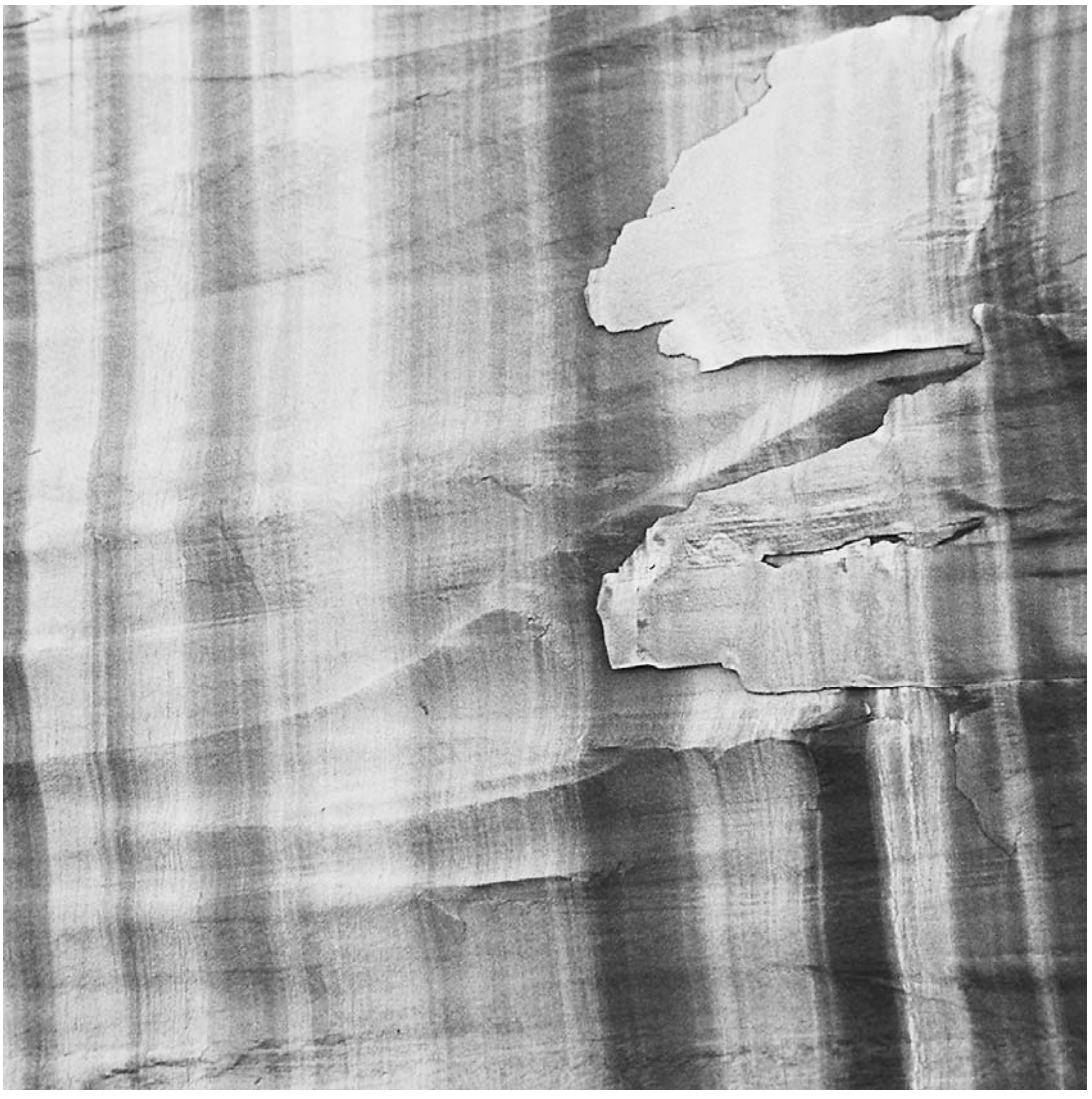
Historical geology, the study of Earth's physical history, is one of the two principal branches of geology, the other being physical geology, or the study of Earth's physical components and the forces that have shaped them. Among the principal subdisciplines of historical geology is stratigraphy, the study of rock layers, which are called strata or, in the singular form, a *stratum.*

Other important subdisciplines include geochronology, the study of Earth's age and the dating of specific formations in terms of geologic time; sedimentology, the study and interpretation of sediments, including sedimentary processes and formations; paleontology, the study of fossilized plants and animals; and paleoecology, the study of the relationship between prehistoric plants and animals and their environments. Several of these subjects are examined in other essays within this book.

EARLY WORK IN STRATIGRAPHY. Among the earliest contributions to what could be called historical geology came from the Italian scientist and artist Leonardo da Vinci (1452–1519), who speculated that fossils might have come from the remains of long-dead animals. Nearly two centuries later, stratigraphy itself had its beginnings when the Danish geologist Nicolaus Steno (1638–1687) studied the age of rock strata.

Steno formulated what came to be known as the law of superposition, or the idea that strata are deposited in a sequence such that the deeper the layer, the older the rock. This, of course, assumes that the rock has been undisturbed, and it is applicable only for one of the three major types of rock, sedimentary (as opposed to igneous or metamorphic). Later, the German geologist Johann Gottlob Lehmann (1719–1767) put forward the theory that certain groups of rocks tend to be associated with each other and that each layer of rock is a sort of chapter in the history of Earth.

Thus, along with Steno, Lehmann helped pioneer the idea of the stratigraphic column, discussed later in this essay. The man credited as the "father of stratigraphy," however, was the English engineer and geologist William Smith (1769–1839). In 1815 Smith produced the first modern geologic map, showing rock strata in England and Wales. Smith's achievement, discussed in Measuring and Mapping Earth, influenced all of geology to the present day by introducing the idea of geologic, as opposed to geographic, map-



Striations visible in sandstone from Neon Canyon, Utah. *(© Rod Planck/Photo Researchers. Reproduced by permission.)*

ping. Furthermore, by linking stratigraphy with paleontology, he formulated an important division of stratigraphy, known as biostratigraphy.

Areas of Stratigraphic Study

Along with biostratigraphy, the major areas of stratigraphy include lithostratigraphy, chronostratigraphy, geochronometry, and magnetostratigraphy. The most basic type of stratigraphy, and the first to emerge, was lithostratigraphy, which is simply the study and description of rock layers. Earth scientists working in the area of lithostratigraphy identify various types of layers, which include (from the most specific to the most general), formations, members, beds, groups, and supergroups.

Biostratigraphy involves the study of fossilized plants and animals to establish dates for and correlate relations between stratigraphic layers. Scientists in this field also identify categories of biostratigraphic units, the most basic being a biozone. Magnetostratigraphy is based on the investigation of geomagnetism and the reversals in Earth's magnetic field that have occurred over time. (See Geomagnetism as well as the discussion of paleomagnetism in Plate Tectonics.)

Chronostratigraphy is devoted to studying the ages of rocks and what they reveal about geologic time, or the vast stretch of history (approximately 4.6 billion years, abbreviated 4.6 Ga) over which Earth's geologic development has occurred. It is concerned primarily with relative dating, whereas geochronometry includes the

determination of absolute dates and time intervals. This typically calls for the use of radiometric dating.

THE STRATIGRAPHIC COLUMN

The stratigraphic column is the succession of rock strata laid down over the course of time, each of which correlates to specific phases in Earth's geologic history. The record provided by the stratigraphic column is most reliable for studying the Phanerozoic, the current eon of geologic history, as opposed to the Precambrian, which constituted the first three eons and hence the vast majority of Earth's geologic history. The relatively brief span of time since the Phanerozoic began (about 545 million years, or Ma) has seen by far the most dramatic changes in plant and animal life. It was in this eon that the fossil record emerged, giving us far more detailed information about comparatively recent events than about a much longer span of time in the more distant past.

RELATIVE AND ABSOLUTE DATING. Precambrian time is so designated because it precedes the Cambrian period, one of 11 periods in the Phanerozoic eon. The Cambrian period extended for about 50 million years, from approximately 545 Ma to 495 Ma ago. This statement in terms of years, however inexact, is an example of absolute age. By contrast, if we say that the Cambrian period occurred at the beginning of the Paleozoic era, after the end of the Proterozoic eon and before the beginning of the Ordovician period, this is a statement of relative age. Both statements are true, and though it is obviously preferable to measure time in absolute terms, sometimes relative terms are the only ones available.

Dating, in scientific terms, is any effort directed toward finding the age of a particular item or phenomenon. Relative dating methods assign an age relative to that of other items, whereas absolute dating determines age in actual years or millions of years. When geologists first embarked on stratigraphic studies, the only means of dating available to them were relative. Using Steno's law of superposition, they reasoned that a deeper layer of sedimentary rock was necessarily older than a shallower layer.

Advances in our understanding of atomic structure during the twentieth century, however, made possible a particularly useful absolute form of dating through the study of radioactive decay. Radiometric dating, which is explained in more detail in Geologic Time, uses ratios between "parent" and "daughter" isotopes. Radioactive isotopes decay, or emit particles, until they become stable, and as this takes place, parent isotopes spawn daughters. The amount of time that it takes for half the isotopes in a sample to stabilize is termed a *half-life.* Elements such as uranium, which has isotopes with half-lives that extend into the billions of years, make possible the determination of absolute dates for extremely old geologic materials.

DIVISIONS OF THE STRATIGRAPHIC COLUMN. Geologic time is divided into named groupings according to six basic units, which are (in order of size from longest to shortest) eon, era, period, epoch, age, and chron. There is no absolute standard for the length of any unit; rather, it takes at least two ages to make an epoch, at least two epochs to compose a period, and so on. The dates for specific eons, eras, periods, and so on are usually given in relative terms, however; an example is the designation of the Cambrian period given earlier.

Chronostratigraphy also uses six time units: the eonothem, erathem, system, series, stage, and chronozone. These time units are analogous to the terms in the geologic time scale, the major difference being that chronostratigraphic units are conceived in terms of relative time and are not assigned dates. The more distant in time a particular unit is, the more controversy exists regarding its boundary with preceding and successive units. This is true both of the geologic and the chronostratigraphic scales.

For this reason, the International Union of Geological Sciences, the leading worldwide body of geologic scientists, has established a Commission on Stratigraphy to determine such boundaries. The commission selects and defines what are called Global Stratotype Sections and Points (GSGPs), which are typically marine fossil formations. Because it is believed that life has existed longest on Earth in its oceans, samples from the water provide the most reliable stratigraphic record.

NAMING OF CHRONOSTRATIGRAPHIC UNITS

As noted, the chronostratigraphic divisions correspond to units of geologic time, even though

chronostratigraphic units are based on relative dating methods and geologic ones use absolute time measures. Because attempts at relative dating have been taking place since the late eighteenth century, today's geologic units originated as what would be called *stratigraphic* or *chronostratigraphic* units. Even today the names of the phases are the same, with the only difference being the units in which they are expressed. Thus, when speaking in terms of geologic time, one would refer to the Jurassic period, whereas in stratigraphic terms, this would be the Jurassic *system.*

In 1759 the Italian geologist Giovanni Arduino (1714–1795) developed the idea of primary, secondary, and tertiary groups of rocks. Though the use of the terms *primary* and *secondary* has been discarded, vestiges of Arduino's nomenclature survive in the modern designation of the Tertiary subera of the Cenozoic era (erathem in stratigraphic terminology) as well as in the name of the present period or system, the Quaternary. (Just as primary, secondary, and tertiary refer to a first, second, and third level, respectively, the term *quaternary* indicates a fourth level.)

We are living in the fourth of four eons, or eonothems, the Phanerozoic, which is divided into three eras, or erathems: Paleozoic, Mesozoic, and Cenozoic. These eras, in turn, are divided into 11 periods, or systems, whose names (except for Tertiary and Quaternary) refer to the locations in which the respective stratigraphic systems were first observed. The names of these systems, along with their dates in millions of years before the present and the origin of their names, are as follows (from the most distant to the most recent):

Periods/Systems of the Paleozoic Era/Erathem

- Cambrian (about 545 to 495 Ma): Cambria, the Roman name for the province of Wales
- Ordovician (about 495 to 443 Ma): Ordovices, the name of a Celtic tribe in ancient Wales
- Silurian (about 443 to 417 Ma): Silures, another ancient Welsh Celtic tribe
- Devonian (about 417 to 354 Ma): Devonshire, a county in southwest England
- Mississippian (a subperiod of the Carboniferous period, about 354 to 323 Ma): the Mississippi River
- Pennsylvanian (a subperiod of the Carboniferous, about 323 to 290 Ma): the state of Pennsylvania
- Permian (about 290 to 248.2 Ma): Perm, a province in Russia

Periods/Systems of the Mesozoic Era/Erathem

- Triassic (about 248.2 to 205.7 Ma): a tripartite, or threefold, division of rocks in Germany
- Jurassic (about 205.7 to 142 Ma): the Jura Mountains of Switzerland and France
- Cretaceous (about 142 to 65 Ma): from a Latin word for "chalk," a reference to the chalky cliffs of southern England and France

Within the more recent Cenozoic era, or erathem, names of epochs (or "series" in stratigraphic terminology) become important. They are all derived from Greek words, whose meanings are given below:

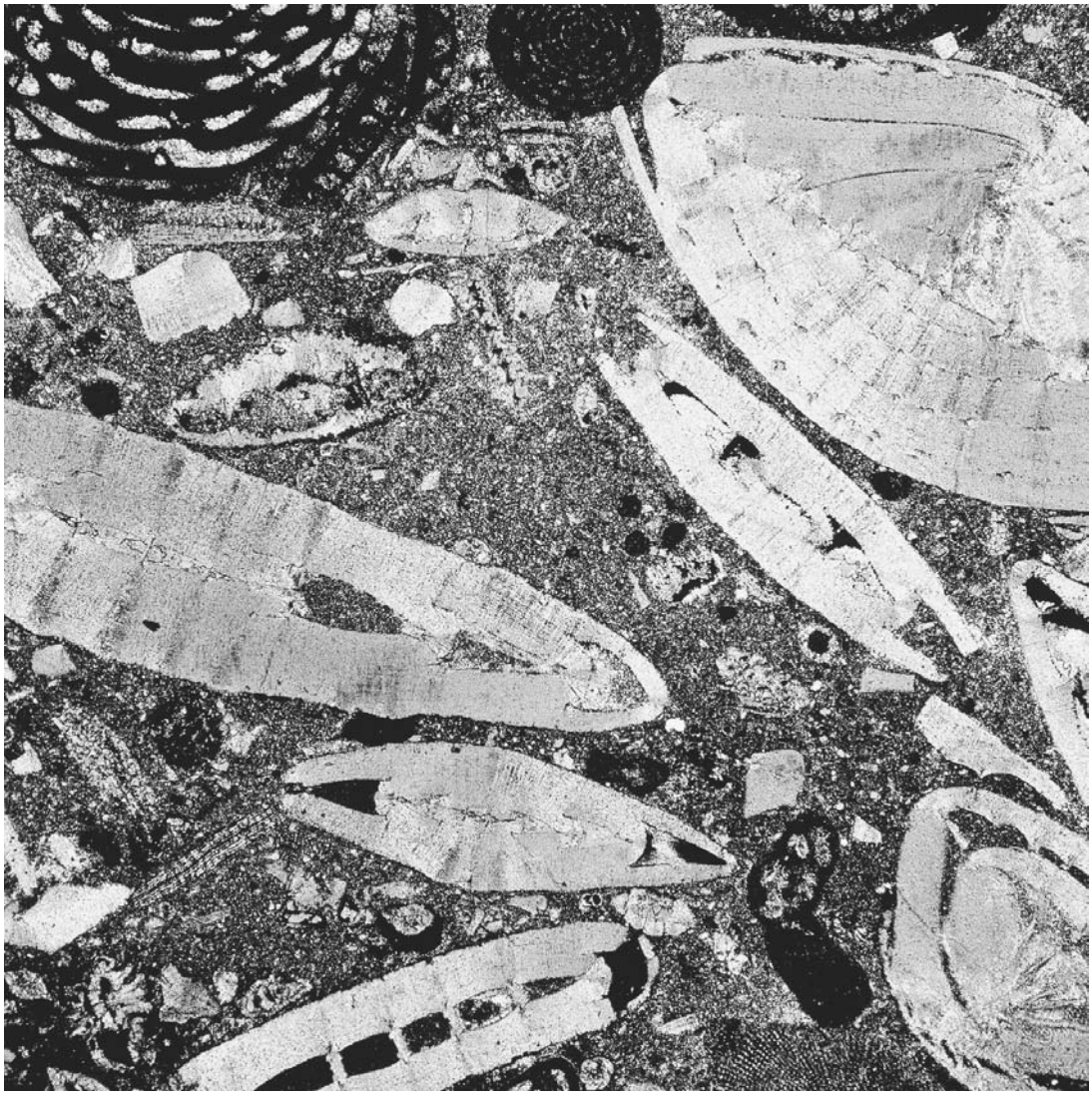
Epochs/Series of the Cenozoic Era/Erathem

- Paleocene (about 65 to 54.8 Ma): "early dawn of the recent"
- Eocene (about 54.8 to 33.7 Ma): "dawn of the recent"
- Oligocene (about 33.7 to 23.8 Ma): "slightly recent"
- Miocene (about 23.8 to 5.3 Ma): "less recent"
- Pliocene (about 5.3 to 1.8 Ma): "more recent"
- Pleistocene (about 1.8 to 0.01 Ma): "most recent"
- Holocene (about 0.01 Ma to present): "wholly recent"

REAL-LIFE APPLICATIONS

CORRELATION

The geologist studying the stratigraphic record is a sort of detective, looking for clues. Just as detectives have their methods for solving crimes, geologists rely on correlation, or methods of establishing age relationships between various strata. There are two basic types of correlation: physical correlation, which requires comparison of the physical characteristics of the strata, and fossil correlation, the comparison of fossil types.



A POLARIZED-LIGHT MICROGRAPH SHOWS FOSSILS IN LIMESTONE DATING TO THE EOCENE AND OLIGOCENE EPOCHS. *(© A. Pasieka/Photo Researchers. Reproduced by permission.)*

Actually, chronostratigraphic work is very similar some of the toughest cases confronted by police detectives, because more often than not the geologic detective has little evidence on which to operate. First of all, as noted earlier, only sedimentary rock can be used in making such determinations: for instance, igneous rock in its molten form, as when it is expelled from a volcano, could force itself underneath a rock stratum, thus confusing the stratigraphic record.

POTENTIAL PITFALLS. Even when the rock is sedimentary, there is still plenty of room for error. The layers may be many feet or less than an inch deep, and it is up to the geologist to determine whether the stratum has been affected by such geologic forces as erosion. If erosion has occurred, it can cause a disturbance, or unconformity (discussed later), which tends to render inaccurate any reading of the stratigraphic record.

Another possible source of disturbance is an earthquake, which could cause one part of Earth's crust to shift over an adjacent section, making the stratigraphic record difficult, if not impossible, to read. Under the best of conditions, after all, the strata are hardly neat, easily defined lines. If one observes a horizontal section, there is likely to be a change in thickness, because as the stratum extends outward, it merges with the edges of adjacent deposits.

Yet another potential pitfall in stratigraphic correlation involves one of the most useful tools

KEY TERMS

ABSOLUTE AGE: The absolute age of a geologic phenomenon is its age in Earth years. Compare with *relative age.*

BIOSTRATIGRAPHY: An area of stratigraphy involving the study of fossilized plants and animals in order to establish dates for and correlations between stratigraphic layers.

CHRONOSTRATIGRAPHY: A subdiscipline of stratigraphy devoted to studying the relative ages of rocks. Compare with *geochronometry.*

CORRELATION: A method of establishing age relationships between various rock strata. There are two basic types of correlation: physical correlation, which requires comparison of the physical characteristics of the strata, and fossil correlation, the comparison of fossil types.

DATING: Any effort directed toward finding the age of a particular item or phenomenon. Methods of geologic dating are either relative (i.e., comparative and usually based on rock strata) or absolute. The latter, based on such methods as the study of radioactive isotopes, usually is given in terms of actual years or millions of years.

EON: The longest phase of geologic time, equivalent to an eonothem in the stratigraphic time scale. Earth's history has consisted of four eons, the Hadean or Priscoan, Archaean, Proterozoic, and Phanerozoic. The next-smallest subdivision of geologic time is the era.

EPOCH: The fourth-longest phase of geologic time, shorter than an era and longer than an age and a chron. An epoch is equivalent to a series in the stratigraphic time scale. The current epoch is the Holocene, which began about 0.01 Ma (10,000 years) ago.

ERA: The second-longest phase of geologic time, after an eon, and equivalent to an erathem in the stratigraphic time scale. The current eon, the Phanerozoic, has had three eras, the Paleozoic, Mesozoic, and Cenozoic, which is the current era. The next-smallest subdivision of geologic time is the period.

EROSION: The movement of soil and rock due to forces produced by water, wind, glaciers, gravity, and other influences.

GA: An abbreviation meaning "gigayears" or "billion years." The age of Earth is about 4.6 Ga.

GEOCHRONOMETRY: An area of stratigraphy devoted to determining absolute dates and time intervals. Compare with *chronostratigraphy.*

GEOLOGIC MAP: A map showing the rocks beneath Earth's surface, including their distribution according to type as well as their ages, relationships, and structural features.

GEOLOGIC TIME: The vast stretch of time over which Earth's geologic development has occurred. This span (about 4.6 billion years) dwarfs the history of human existence, which is only about two million years. Much smaller still is the span of human civilization, only about 5,500 years.

KEY TERMS CONTINUED

HISTORICAL GEOLOGY: The study of Earth's physical history. Historical geology is one of two principal branches of geology, the other being physical geology.

ISOTOPES: Atoms that have an equal number of protons, and hence are of the same element, but differ in their number of neutrons. This results in a difference of mass. An isotope may be either stable or radioactive.

LAW OF FAUNAL SUCCESSION: The principle that all samples of any given fossil species were deposited on Earth, regardless of location, at more or less the same time. This makes it possible to correlate widely separated strata.

LAW OF SUPERPOSITION: The principle that strata are deposited in a sequence such that the deeper the layer, the older the rock. This is applicable only or sedimentary rock, as opposed to igneous or metamorphic rock.

LITHOSTRATIGRAPHY: An area of stratigraphy devoted to the study and description (but not the dating) of rock layers.

MA: An abbreviation used by earth scientists, meaning "million years" or "megayears." When an event is designated as, for instance, 160 Ma, it usually means 160 million years ago.

PALEONTOLOGY: The study of fossilized plants and animals, or flora and fauna.

PERIOD: The third-longest phase of geologic time, after an era; it is equivalent to a system in the stratigraphic time scale. The current eon, the Phanerozoic, has had 11 periods, and the current era, the Cenozoic, has consisted of three periods, of which the most recent is the Quaternary. The next-smallest subdivision of geologic time is the epoch.

PRECAMBRIAN TIME: A term that refers to the first three of four eons in Earth's history, which lasted from about 4,560 Ma to about 545 Ma ago.

RADIOACTIVITY: A term describing a phenomenon whereby certain materials are subject to a form of decay brought about by the emission of high-energy particles or radiation. Forms of particles or energy include alpha particles (positively charged helium nuclei), beta particles (either electrons or subatomic particles called positrons), or gamma rays, which occupy the highest energy level in the electromagnetic spectrum.

RADIOMETRIC DATING: A method of absolute dating using ratios between "parent" isotopes and "daughter" isotopes, which are formed by the radioactive decay of parent isotopes.

RELATIVE AGE: The relative age of a geologic phenomenon is its age compared with the ages of other geologic phenomena, particularly the stratigraphic record of rock layers. Compare with *absolute age.*

KEY TERMS CONTINUED

SEDIMENT: Material deposited at or near Earth's surface from a number of sources, most notably preexisting rock.

SEDIMENTARY ROCK: Rock formed by compression and deposition (i.e., formation of deposits) on the part of other rock and mineral particles. Sedimentary rock is one of the three major types of rock, along with igneous and metamorphic.

SEDIMENTOLOGY: The study and interpretation of sediments, including sedimentary processes and formations.

STRATA: Layers, or beds, of rocks beneath Earth's surface. The singular form is *stratum.*

STRATIGRAPHIC COLUMN: The succession of rock strata laid down over the course of time, each of which correlates to specific junctures in Earth's geologic history.

STRATIGRAPHY: The study of rock layers, or strata, beneath Earth's surface.

UNCONFORMITY: An apparent gap in the geologic record, as revealed by observing rock layers or strata.

WEATHERING: The breakdown of rocks and minerals at or near the surface of Earth due to physical or chemical processes, or both.

available to a geologist attempting to find an absolute age for the materials he or she is studying: radiometric dating. Though this method can provide accurate absolute dates, it is quite possible that the age thus determined will be the age of the parent rock from which a sample is taken, not the age of the sample itself. The grains of sand in a piece of sandstone, for instance, are much older than the larger unit of sandstone, and for this reason, radiometric dating is useful only in specific circumstances.

PHYSICAL AND FOSSIL CORRELATION. Given all these challenges, it is a wonder that geologists manage to correlate strata successfully, yet they do. Physical correlations are achieved on the basis of several criteria, including color, the size of grains, and the varieties of minerals found within a stratum. By such means, it is sometimes possible to correlate widely separated strata.

Particularly impressive feats of correlation can result from the study of fossils, whose stratigraphic implications, as we have noted, were first discovered by William Smith. Smith hit upon the idea of biostratigraphy while excavating land for a set of canals near London. As he discovered, any given stratum contains the same types of fossils, and strata in two different areas thus can be correlated.

Long before his countryman Charles Darwin (1809–1882) developed the theory of evolution, Smith conceived his own law of faunal succession, which hints at the idea that species developed and disappeared over given phases in Earth's past. According to the law of faunal succession, all samples of any given fossil species were deposited on Earth, regardless of location, at more or less the same time. As a result, if a geologist finds a stratum in one area that contains a particular fossil and another in a distant area containing the same fossil, it is possible to conclude that the strata are the same.

UNCONFORMITIES

In discussing the many challenges facing a geologist studying stratigraphic data, the role of erosion was noted. Let us return to that subject, because erosion is a source of what are known as unconformities, or gaps in the rock record. Unconformities are of three types: angular unconformities, disconformities, and nonconformities.

Angular unconformities involve a tilting of the layers, such that an upper layer does not lie perfectly parallel to a lower one. Disconformities

are more deceptive, because the layers are parallel, yet there is still an unconformity between them, and only a study of the fossil record can reveal the unconformity. Finally, a nonconformity arises when sedimentary rocks are divided from a type of igneous rock known as *intrusive* (meaning "cooled within Earth").

ANGULAR UNCONFORMITIES. Angular unconformities emerge as a by-product of the dramatic shifts and collisions that take place in plate tectonics (see Plate Tectonics). Sediment accumulates and then, as a result of plate movement, is moved about and eventually experiences weathering and erosion. Layers are tilted and then flattened by more erosion, and as the solid earth rises or sinks, they are shifted further. Such is the case, for instance, along the Colorado River at the Grand Canyon, where angular unconformities reveal a series of movements over the years.

Another famous angular unconformity can be found at Siccar Point in Scotland, where nearly horizontal deposits of sandstone rest atop nearly vertical ones of graywacke, another sedimentary rock. Observations of this unconformity led the great geologist James Hutton (1726–1797) to the realization that Earth is much, much older than the 6,000 years claimed by theologians in his day (see Historical Geology).

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PALEONTOLOGY

CONCEPT

Thanks to a certain 1993 blockbuster, most people know the name of at least one period in geologic history. *Jurassic Park* spurred widespread interest in dinosaurs and, despite its fantastic plot, encouraged popular admiration and respect for the work of paleontologists. Paleontology is the study of life-forms from the distant past, as revealed primarily through the record of fossils left on and in the earth. It is a complex and varied subdiscipline of historical geology that is tied closely to the biological sciences. As with other types of historical geology, the work of a paleontologist is similar to that of a detective investigating a case with few and deceptive clues. Reliable fossil samples are more rare, compared with the vast number of species that have lived on Earth, than one might imagine. Furthermore, several factors pose challenges for paleontologists attempting to interpret the fossil record. Nonetheless, paleontologic research has led to a growing understanding of how life emerged, how Earth has changed, and how vast animal populations became extinct over relatively short periods of time.

HOW IT WORKS

Thinking in Terms of Geologic Time

The term geologic time refers to the great sweep of Earth's history, a timescale that dwarfs the span of human existence. The essays Historical Geology and Geologic Time offer several comparisons to emphasize the proportions involved and to illustrate the very short period during which human life has existed on this planet.

As one example shows, if all of geologic time were compressed into a single year, the first *Homo sapiens* would have appeared on the scene at about 8:00 p.m. on December 31. Human civilization, which dates back about 5,500 years (a millennium before the building of Egypt's great pyramids) would have emerged within the last minute of the year.

In another example, geologic time is compared to the distance from Los Angeles to New York City. On this scale, the period of time in which humans have existed on the planet would be equivalent to the distance from New York's Central Park to the Empire State Building, or less than 2 mi. (3.2 km). The history of human civilization, on the other hand, would be less than 16 ft. (4.9 m) long.

THE "ABYSS OF TIME." Needless to say, the scope of geologic time compared with the units with which we are accustomed to measuring our lives (or even the history of our civilization) is more than a little intimidating. This fact perhaps was best expressed by the Scottish geologist John Playfair (1748–1819), friend and countryman of the "father of geology," James Hutton (1726–1797). At a time when many people were content to believe that the Earth had been around no more than 6,000 years (see Historical Geology), Hutton suggested that to undergo the complex processes that had shaped its landforms, the planet had to be much, much older. Commenting on Hutton's discoveries, Playfair said, "The mind seemed to grow giddy by looking so far into the abyss of time."



The head of a Tyrannosaurus rex ("king of the terrible lizards") found in Montana, dating to the Mesozoic period. *(© Tom McHugh/Photo Researchers. Reproduced by permission.)*

Carbon: The Meaning of "Life"

A discussion of life on Earth requires us to go deep into this "abyss," though not nearly as far back as the planet's origins. It does appear that life on Earth existed at a very early point, but in this context "life" refers merely to molecules of carbon-based matter capable of replicating themselves. Knowledge of these very early forms is extremely limited.

Carbon appears in all living things, in things that were once living, and in materials produced by living things (for example, sap, blood, and urine). Hence, the term *organic,* which once meant only living matter, refers to almost all types of material containing carbon. The only carbon-containing materials that are not considered organic are oxides, such as carbon dioxide and carbon monoxide, and carbonates, a class of minerals that is extremely abundant on Earth.

Precambrian Time

We will return to the subject of carbon, which plays a role in one technique for dating relatively recent items or phenomena. For the present, however, let us set our bearings for a discussion of the Phanerozoic eon, the fourth and last of the major divisions of geologic time. Though extremely primitive life-forms existed before the Phanerozoic eon, the vast majority of species have evolved since it began, and consequently paleontological work is concerned primarily with the Phanerozoic eon.

The divisions of geologic time are not arranged in terms of strict mathematical relationships of the type to which we are accustomed, for example, ten years in a decade, ten decades in a century, and so on. Instead, each era consists of two or more periods, each period consists of two or more epochs, and so on. The first 4,000 million years or so of Earth's existence (abbreviated as 4,000 Ma, or 4 Ga) are known as Precambrian time. In discussing this period of time, the vast majority of the planet's history, it is seldom necessary to speak of geologic time divisions smaller than the largest unit, the eon. Precambrian time consisted of three eons, the Hadean or Priscoan, Archaean, and Proterozoic.

The first three eons. The Hadean (sometimes called the Priscoan and dating to about 4,560 Ma to 4,000 Ma ago) saw the formation of the planet and the beginnings of the oceans and an early form of atmosphere that consisted primarily of carbon dioxide. It was during this eon that the carbon-based matter

referred earlier made its appearance, perhaps by means of the meteorites that bombarded the planet during that long-ago time.

In the Archaean eon (about 4,000 Ma to 2,500 Ma ago) the first clear evidence of life appeared in the form of microorganisms. These were prokaryotes, or cells without a nucleus, which eventually were followed by eukaryotes, or cells with a nucleus. Many of the prerequisites for life as we know it were established during this time, though our present oxygen-containing atmosphere still lay far in the future.

Longest of the four eons was the Proterozoic eon (about 2,500 Ma to 545 Ma). This phase saw the beginnings of very basic forms of plant life, while oxygen in the atmosphere assumed about 4% of its present levels. Animal life, meanwhile, still consisted primarily of eukaryotes.

The Phanerozoic Eon

The majority of paleontologic history has taken place during the Phanerozoic eon. In the course of this essay, we discuss its eras and periods (the second- and third-longest spans of geologic time, respectively) as they relate to life on Earth. The three Phanerozoic eras are as follows:

Eras of the Phanerozoic Eon

- Paleozoic (about 545–248.2 Ma)
- Mesozoic (about 248.2–65 Ma)
- Cenozoic (about 65 Ma–present)

Within these eras are the following periods:

Periods of the Paleozoic Era

- Cambrian (about 545–495 Ma)
- Ordovician (about 495–443 Ma)
- Silurian (about 443–417 Ma)
- Devonian (about 417–354 Ma)
- Carboniferous (about 354–290 Ma)
- Permian (about 290–248.2 Ma)

Periods of the Mesozoic Era

- Triassic (about 248.2–205.7 Ma)
- Jurassic (about 205.7–142 Ma)
- Cretaceous (about 142–65 Ma)

Periods of the Cenozoic Era

- Palaeogene (about 65–23.8 Ma)
- Neogene (about 23.8–1.8 Ma)
- Quaternary (about 1.8 Ma to the present)

The Carboniferous period of the Paleozoic era usually is divided into two subperiods, the Mississippian (about 354 to 323 Ma) and the Pennsylvanian (about 323–290 Ma). In addition, the Palaeogene and Neogene periods of the Cenozoic era often are lumped together as a subera called the Tertiary. By substituting that name for those of the two periods, it is possible to use a time-honored mnemonic device by which geology students have memorized the names of the 11 Phanerozoic periods: "Camels Ordinarily Sit Down Carefully; Perhaps Their Joints Creak Tremendously Quietly."

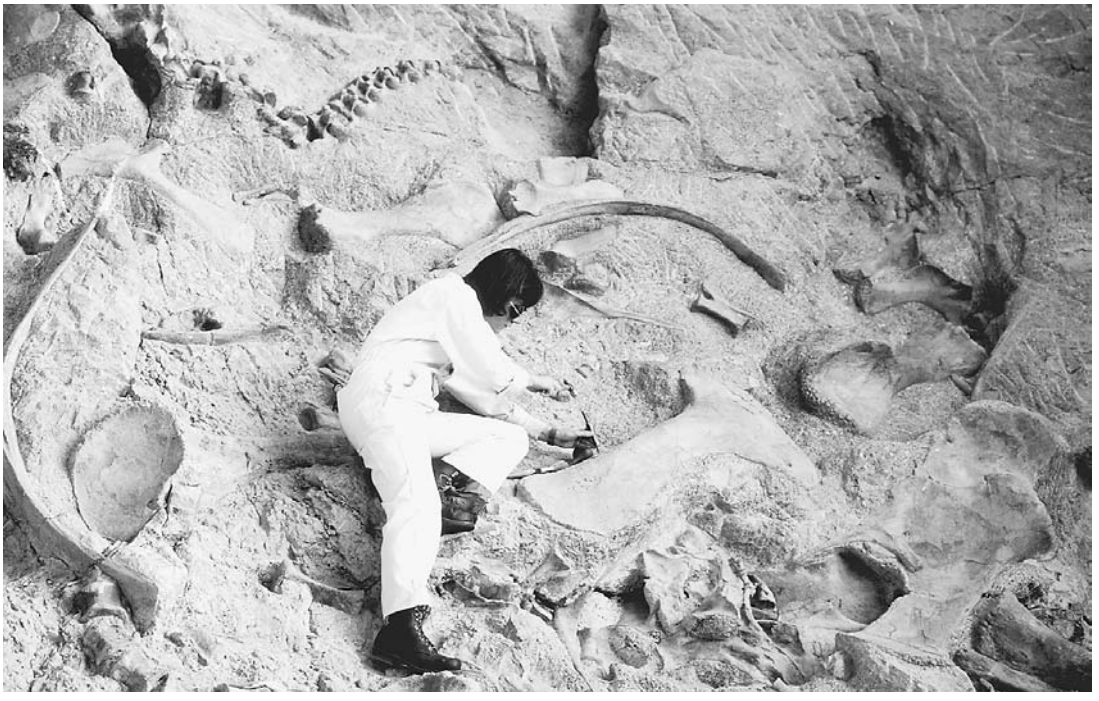
Epochs of the Cenozoic era. An epoch is the fourth-largest division of geologic time and is, for the most part, the smallest one with which we will be concerned. (There are two smaller categories, the age and the chron.) Listed here are the epochs of the Cenozoic era from the most distant to the Holocene, in which we are now living. Their names are derived from Greek words whose meanings are provided:

Epochs of the Cenozoic Era

- Paleocene (about 65–54.8 Ma): "early dawn of the recent"
- Eocene (about 54.8–33.7 Ma): "dawn of the recent"
- Oligocene (about 33.7–23.8 Ma): "slightly recent"
- Miocene (about 23.8–5.3 Ma): "less recent"
- Pliocene (about 5.3–1.8 Ma): "more recent"
- Pleistocene (about 1.8–0.01 Ma): "most recent"
- Holocene (about 0.01 Ma to present): "wholly recent"

A Brief Overview of Paleontologic History

The title "A Brief Overview of Paleontologic History" is almost a contradiction in terms, since virtually nothing about the history of Earth has been brief. Moreover, the history of *life* on Earth is so filled with detail and complexity that it could fill many books, as indeed it has. Owing to that complexity, anything approaching an exhaustive treatment of the subject would burden the reader with so much technical terminology that it would obscure the larger overview of paleontology and the materials of the paleontologist's work. Therefore, only the most cursory of treatments is possible, or indeed warranted, in the present context. For additional detail, the reader is invited to consult other texts, including



A DINOSAUR IS EXCAVATED AT DINOSAUR NATIONAL MONUMENT IN COLORADO. *(© James L. Amos/Photo Researchers. Reproduced by permission.)*

those listed in the suggested reading section at the end of this essay.

As with many another process, the evolution of organisms was exceedingly slow in the beginning (and here the comparative term *slow* refers even to the standards of geologic time), but it sped up considerably over the course of Earth's history. This is not to suggest that the development of life-forms has been a steady process; on the contrary, it has been punctuated by mass extinctions, discussed at the conclusion of this essay. Nonetheless, it is correct to say that during the first 80%–90% of Earth's history, the few existing life-forms underwent an extremely slow process of change.

PRECAMBRIAN AND PALEOZOIC LIFE-FORMS. Life existed in Precambrian time, as noted, but over the course of those four billion years, it evolved only to the level of single-cell microorganisms. Samples of these organisms have been found in the fossil record, but the fossilized history of life on Earth really began in earnest only with the Cambrian period at the beginning of the Paleozoic era and the Phanerozoic eon. The early Cambrian period saw an explosion of invertebrate (without an internal skeleton) marine forms, which dominated from about 545 Ma–417 Ma ago. By about 420 Ma–410 Ma, life had appeared on land, in the form of algae and primitive insects.

The beginning of the Devonian period (approximately 417 Ma) saw the appearance of the first vertebrates (animals with an internal skeleton), which were jawless fish. Plant life on land consisted of ferns and mosses. By the late Devonian (about 360 Ma), fish had evolved jaws, and amphibians had appeared on land. Reptiles emerged between about 320 Ma and 300 Ma, in the Pennsylvanian subperiod of the Carboniferous. In the last period of the Paleozoic era, the Permian (about 290–248.2 Ma), reptiles became the dominant land creatures.

MESOZOIC AND CENOZOIC LIFE-FORMS. The next era, the Mesozoic (about 248.2–65 Ma), belonged to a particularly impressive form of reptile, known as the terrible lizard: the dinosaur. These creatures are divided into groups based on the shape of their hips, which were either lizardlike or birdlike. Though the lizardlike Saurischia emerged first, they lived alongside the birdlike Ornithischia throughout the late Triassic, Jurassic, and Cretaceous periods. Ornithischia were all herbivores, or plant eaters, whereas Saurischia included both herbivores and carnivores, or meat eaters. Naturally, the most fierce of the dinosaurs were carnivores, a group

that included the largest carnivore ever to walk the earth, *Tyrannosaurus.*

Though dinosaurs receive the most attention, the Mesozoic world was alive with varied forms, including flying reptiles and birds. (In fact, dinosaurs may have been related to birds, and, in the opinion of some paleontologists, they may have been warm-blooded, like birds and mammals, rather than cold-blooded, like other reptiles.) Botanical life included grasses, flowering plants, and trees of both the deciduous (leaf-shedding) and coniferous (cone-bearing) varieties.

A violent event, discussed in the context of mass extinction later in this essay, brought an end to the Mesozoic era. This cleared the way for the emergence of mammalian forms at the beginning of the Cenozoic, though it still would be a long time before anything approaching an ape, let alone a human, appeared on the scene. The earliest hominid, or humanlike creature, dates back to about four million years ago, in the Pliocene epoch of the Neogene period.

Historical Geology and Paleontology

One of the two principal divisions of geology (along with physical geology) is historical geology, the study of Earth's physical history. Other subdisciplines of historical geology are stratigraphy, the study of rock layers, or strata, beneath Earth's surface; geochronology, the study of Earth's age and the dating of specific formations in terms of geologic time; and sedimentology, the study and interpretation of sediments, including sedimentary processes and formations.

Paleontology, the investigation of life-forms from the distant past (primarily through the study of fossilized plants and animals), is another subdiscipline of historical geology. Though it is rooted in the physical sciences, it obviously crosses boundaries into the biological or life sciences as well. Related or subordinate fields include paleozoology, which focuses on the study of prehistoric animal life; paleobotany, the study of past plant life; and paleoecology, the study of the relationship between prehistoric plants and animals and their environments.

Classifying Plants and Animals

Given the close relationship between paleontology and the biological sciences, it is necessary to discuss briefly the taxonomic system applied in biology, botany, zoology, and related fields. Taxonomy is an area of biology devoted to the identification, classification, and naming of organisms. Devised in the eighteenth century by the Swedish botanist Carolus Linnaeus (1707–1778) and improved in succeeding years by many others, the taxonomic system revolutionized biology.

Linnaeus's taxonomy provided a framework for classifying known species not simply by superficial similarities but also by systemic characteristics. For example, worms and snakes have something in common on a surface level, because they are both without appendages and move by writhing on the ground. A worm is an invertebrate, however, whereas a snake is a vertebrate. The Linnaean system therefore would classify them in widely separated categories: they are not siblings or even first cousins but more like fourth cousins.

Moreover, the system created by Linnaeus gave scientists a means for classifying and thereby potentially understanding much about the history and characteristics of species as yet undiscovered. Thus, it would prove of immeasurable significance to the English naturalist Charles Darwin (1809–1882) in formulating his theory of evolution. As Darwin showed, the varieties of different organisms have increased over time, as those organisms developed characteristics that made them more adaptable to their environments. Plants and animals that failed to adapt simply became extinct, though failure to adapt is only one of several causes for extinction, as we shall see.

A brief overview. The Linnaean system uses binomial nomenclature, or a two-part naming scheme (in Latin), to identify each separate type of organism. If a man is named John Smith, then "Smith" identifies his family, while John identifies him singularly. Likewise each variety of organism is identified by genus, equivalent to Smith, and species, analogous to John. In the Linnaean system, there are eight levels of classification, which, from most general to most specific, are kingdom, phylum, subphylum, class, order, family, genus, and species.

These levels can be illustrated by identifying a species near and dear to all of us: *Homo sapiens,* commonly known as *humans.* We belong to the animal kingdom (Animalia), the Chordata (i.e., possessing some form of central nervous system) phylum, and the Vertebrata subphylum, indicating the existence of a backbone. Within the mammal (Mammalia) class we are part of the primate (Primata) order, along with apes. Humans are distinguished further as members of the hominid (Hominoidea), or "human-like" family; the genus *Homo* ("man"); and the species *sapiens* ("wise").

Dating Materials From the Past

In studying the past, paleontologists and other earth scientists working in the field of historical geology rely on a variety of dating techniques. "Dating," in a scientific context, usually refers to any effort directed toward finding the age of a particular item or phenomenon. It may be relative, devoted to finding an item's age in relation to that of other items; or absolute, involving the determination of age in actual years or millions of years.

Among the methods of relative dating are stratigraphic dating, discussed in the essay Stratigraphy, as well as seriation, faunal dating, and pollen dating. Seriation entails analyzing the abundance of a particular item and assigning relative dates based on that abundance. Faunal dating is the use of bones from animals (fauna) to determine age, and pollen dating, or palynology, analyzes pollen deposits.

FAUNAL DATING AND PALYNOLOGY. The concept of faunal dating emerged from early work by the English engineer and geologist William Smith (1769–1839), widely credited as the "father of stratigraphy." In particular, Smith established an important division of stratigraphy, known as biostratigraphy, that is closely tied to paleontology. While excavating land for a set of canals near London, he discovered that any given stratum, or rock layer, contains the same types of fossils, and therefore strata in two different areas can be correlated.

Smith stated this in what became known as the law of faunal succession: all samples of any given fossil species were deposited on Earth, regardless of location, at more or less the same time. As a result, if a geologist finds a stratum in one area that contains a particular fossil and another in a distant area containing the same fossil, it is possible to conclude that the strata are the same.

Pollen dating, or palynology, is based on the fact that seed-bearing plants release large numbers of pollen grains each year. As a result, pollen spreads over the surrounding area, and in many cases pollen from the distant past has been preserved. This has occurred primarily in lake beds, peat bogs, and, occasionally, in areas with cool or acidic soil. By observing the species of pollen deposited in an area, scientists are able to develop a sort of "pollen calendar," which provides information about such details as changes in climate.

DENDROCHRONOLOGY. Scientists use relative dating when they must, but they would prefer to determine dates in an absolute sense wherever possible. Most methods of absolute dating rely on processes that are not immediately comprehensible to the average person, but there is one exception: dendrochronology, or the dating of tree rings. As almost everyone knows, trees produce one growth ring per year. There is nothing magical about this, since a year is not an abstract unit of time; rather, it is based on Earth's revolution around the Sun, during which time the planet undergoes changes in orientation that result in the four seasons, which, in turn, affect the tree's growth.

Though dendrochronology makes use of a principle familiar to most people, the work of the dendrochronologist requires detailed, often complex study. Just as the layers of rock beneath Earth's surface reveal information about past geologic events (a matter discussed in the essay Stratigraphy), tree rings can tell us much about environmental changes. Thin rings, for instance, suggest climatic anomalies and may provide clues about cataclysmic events that were understood only vaguely by the ancient humans who experienced them. (An example of this is the apparent cataclysm of A.D. 535, which is discussed Earth Systems.)

AMINO-ACID RACIMIZATION. Dendrochronology is useful only for studying the relatively recent past, up to about 10,000 years—a span equivalent to the Holocene epoch, which began with the end of the last ice age. To investigate more distant phases of Earth's history, it is necessary to use forms of radiometric dating, which we will discuss shortly. The principles of

radiometric dating, however, are illustrated by another method, amino-acid racimization.

With the exception of some microbes, living organisms incorporate only one of two forms of amino acids, known as L-forms. Once the organism dies, the L-amino acids gradually convert to D-amino acids. In the 1960s, scientists discovered that by comparing the ratios between the L- and D-forms, it was possible to date organisms that were several thousand years old. Unfortunately, it has since come to light that because of the many factors affecting the rate of amino-acid conversion, this method is less reliable than once was believed. Moisture, temperature, and pH (the relative acidity and alkalinity of a substance) all play a part, and because these factors vary so widely, amino-acid racimization no longer is used commonly.

Nonetheless, the basic principle behind amino-acid racimization plays a part in other, more reliable forms of absolute dating. Many of them are based on the fact that over time, a particular substance converts to another, mirror substance. By comparing the ratios between them, it is possible to arrive at some estimate of the amount of time that has elapsed since the organism died.

RADIOCARBON DATING. The most significant method of absolute dating available to scientists today is radiometric dating, which is explained in detail in the essay Geologic Time. Each chemical element is distinguished by the number of protons (positively charged particles) in its atomic nucleus, but atoms of a particular element may have differing numbers of neutrons, or neutrally charged particles, in their nuclei. Such atoms are referred to as isotopes.

Certain isotopes are stable, whereas others are radioactive, meaning that they are likely to eject particles from the nucleus over time. The amount of time it takes for half the isotopes in a sample to stabilize is called its half-life. By analyzing the quantity of radioactive isotopes in a given sample that have converted to stable isotopes, it is possible to determine the age of the sample. In other situations, it is necessary to compare ratios of unstable "parent" isotopes to even more unstable "daughter" isotopes produced by the parent.

As we noted earlier, carbon is present in all living things, and thus an important means of dating available to paleontologists uses a radioactive form of carbon. All atoms of carbon have six protons, and the most stable and abundant carbon isotope is carbon-12, so designated because it has six neutrons. On the other hand, carbon-14, with eight neutrons, is unstable.

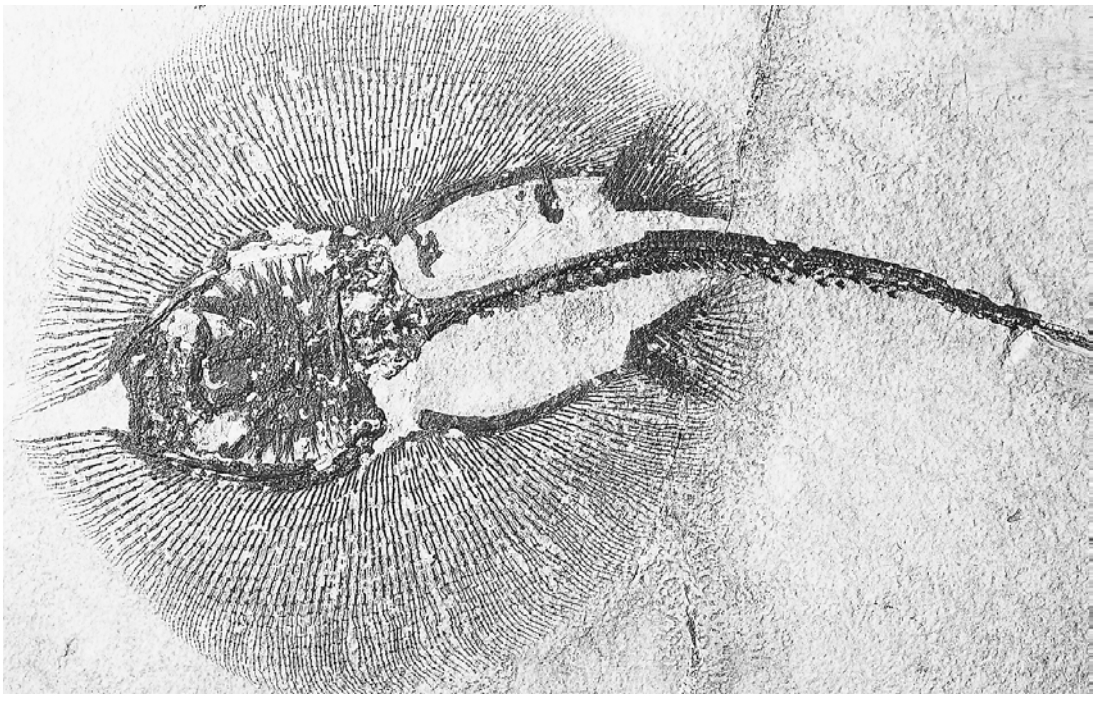
When an organism is alive, it incorporates a certain ratio of carbon-12 in proportion to the (very small) amount of carbon-14 that it receives from the atmosphere. Once the organism dies, however, it stops incorporating new carbon, and the ratio between carbon-12 and carbon-14 begins to change as the carbon-14 decays to form nitrogen-14. Therefore, a scientist can use the ratios of carbon-12, carbon-14, and nitrogen-14 to estimate the age of an organic sample. This method is known as radiocarbon dating.

Carbon-14, or radiocarbon, has a half-life of 5,730 years, meaning that it is useful for analyzing only fairly recent samples. Nonetheless, it takes much longer than 5,730 years for the other half of the radiocarbon isotopes in a given sample to stabilize, and for this reason radiocarbon dating can be used with considerable accuracy for 30,000–40,000 years. Sophisticated instrumentation can extend this range even further, up to 70,000 years.

THE LIMITS OF ABSOLUTE DATING. While 70,000 years, or 0.07 Ma, may be a long time in human terms, from the standpoint of the earth scientist, 0.07 Ma is only yesterday—the latter part of the last epoch, the Pleistocene. Other forms of radiometric dating, such as potassium-argon dating and uranium-series dating, can be used to measure truly long spans of times, in the billions of years. These methods are discussed in Geologic Time.

Potassium-argon dating and uranium-series dating can be useful to the paleontologist, inasmuch as they aid in determining the age of the geologic samples in which the remains of life-forms are found. Nothing is simple, however, when it comes to dating specimens from the distant past. After all, geologists working in the realm of stratigraphy face numerous challenges in judging the age of samples, even with these sophisticated forms of radiometric dating. (For more on this subject, see Stratigraphy.)

In fact, the work of a paleontologist is much like that of the stratigrapher. The success of either type of scientist relies more on detailed and painstaking detective work than it does on sophisticated technology. Both must analyze lay-



Stingray fossil, possibly dating to the Jurassic period. This is a rare find, because stingrays have no bone, only cartilage, which makes it harder for them to undergo mineralization and be preserved as fossils. *(© Gary Retherford/Photo Researchers. Reproduced by permission.)*

ered samples from the past to form a picture of the chronology in which the samples evolved, and oftentimes the apparent evidence can be deceptive. The principal difference between stratigraphic and paleontologic study relates to the materials: rocks in the first instance and fossils in the second.

Real-Life Applications

Fossils and Fossilization

The term fossil refers to the remains of any prehistoric life-form, especially those preserved in rock before the end of the last ice age. The process by which a once-living thing becomes a fossil is known as fossilization. Generally, fossilization refers to changes in the hard portions, including bones, teeth, shells, and so on. This series of changes, in which minerals are replaced by different minerals, is known as mineralization. Sometimes, soft parts may experience mineralization and thus be preserved as fossils. A deceased organism in the process of becoming a fossil is known as a subfossil.

The majority of fossils come from invertebrates, such as mussels, that possess hard parts. Generally speaking, the older and smaller the organism, the more likely it is to have experienced fossilization, though other factors (which we will discuss later) also play a part. One of the most important factors involves location: for the most part, the lower the altitude, the greater the likelihood that a region will contain fossils. The best place of all is in the ocean, particularly the ocean floor. Nonetheless, fossils have been found on every continent of Earth, and the great distances that sometimes separate samples of the same species have aided earth scientists of many fields in understanding the processes that shaped our planet.

Fossils and geologic history. The earth beneath our feet is not standing still; rather, it is constantly moving, and over the great stretches of geologic time, the positions of the continents have shifted considerably. The details of these shifts are discussed in Plate Tectonics, an area of geologic study that explains much about the earth, from earthquakes and volcanoes to continental drift.

Paleontology has contributed to the study of plate tectonics by revealing apparent anomalies,

such as fossilized dinosaur parts in Antarctica. No dinosaur could have lived on that forbidding continent, so there must be some other explanation: the continental plates themselves have moved. Long ago, the present continents were united in a "supercontinent" called Pangaea. When Pangaea split apart to form the present continents, the remains of various species were separated from one another and from the latitudes to which they were accustomed in life.

Fossilized remains of single-cell organisms have been found in rock samples as old as 3.5 Ga, and animal fossils have been located in rocks that date to the latter part of Precambrian time, as old as 1 Ga. Just as paleontologists have benefited from studies in chronostratigraphy and geochronometry, realms of stratigraphy concerned with the dating of rock samples, stratigraphers and other geologists have used fossil samples to date the rock strata in which they were found. Not all fossilized life-forms are equally suited to this purpose. Certain ones, known as index fossils or indicator species, have been associated strongly with particular intervals of geologic time. An example is the ammonoid, a mollusk that proliferated for about 350 Ma from the late Devonian to the early Cretaceous before experiencing mass extinction.

MAKING THE GRADE AS A FOSSIL. Everything that is living eventually dies, but not nearly all living things will become fossils. And even if they do, there are numerous reasons why fossils might not be preserved in such a way as to provide meaningful evidence for a paleontologist many millions of years later. In the potential pool of candidates for fossilization, as we have noted, organisms without hard structural portions are unlikely to become fossilized. Fossilization of soft-bodied creatures sometimes occurs, however, as, for instance, at Burgess Shale in British Columbia, where environmental conditions made possible the preservation of a wide range of samples.

Furthermore, location is a powerful factor. Sedimentary rock, formed by compression and deposition (i.e., formation of deposits) on the part of other rock and mineral particles, provides the setting for many fossils. Best of all is sediment, such as sand or mud, that has not yet consolidated into harder sandstone, limestone, or other rocks. Organisms that die in upland locations are more likely to be disturbed either by wind or by scavengers, creatures that feed on the remains of living things. On the other hand, an organism at the bottom of an ocean is out of reach from most scavengers. Even at lesser depths, if the organism is in a calm, relatively scavenger-free marine environment, there is a good chance that it will be preserved.

Assuming that all the conditions are right and the dead organism is capable of undergoing fossilization, it will experience mineralization of one type or another. Living things already contain minerals, which is the reason why people take mineral supplements to augment the substances nature has placed in their bodies to preserve and extend life. In the mineralization of a fossil, the minerals in the organism's body may be replaced by other ones, or other minerals may be added to existing ones. It is also possible that both the hard and soft parts will dissolve and be replaced by a mineral cement that forms a mold that preserves the shape of the organism.

FINDING AND STUDYING FOSSILS. Only about 30% of species are ever fossilized, a fact that scientists must take into account, because it could skew their reading of the paleontologic record. If a paleontologist judges the past only from the fossils that have been found in an area, it will result in a picture of a past environment that contained only certain species, when, in fact, others were present. Furthermore, there are many factors that contribute to the loss of fossils. For instance, if the area has been subjected to violent tectonic activity, it is likely that the sample will be destroyed partially or wholly.

The removal of a fossil from its home in the rock is a painstaking process akin to restoring a valuable piece of art. Before removing it, the paleontologist photographs the fossil and surrounding strata and records details about the environment. Only when these steps have been taken is the fossil removed. This is done with a rock saw, which is used to cut out carefully a large area surrounding the fossil. The sample is then jacketed, or wrapped in muslin with an additional layer of wet plaster, and taken to a laboratory for study.

Fossil research can reveal a great deal about the history of life on Earth, including the relationships between species or between species and their habitats. Studies of dinosaur bones have brought to light proteins that existed in the bod-

ies of these long-gone creatures, while research on certain oxygen isotopes has aided attempts to discover whether dinosaurs were warm-blooded creatures. Thanks to advances in the understanding of DNA (deoxyribonucleic acid), which provides the genetic codes for all living things, it may be possible to make even more detailed studies in the future.

Mass Extinction

The remains of dinosaurs, of course, have an importance aside from their significance to paleontology. The bodies of these giant lizards have been deposited in the earth, where over time they became coal, peat, petroleum, and other fossil fuels. The latter are discussed in Economic Geology, but the fact that the dinosaurs disappeared at all is of particular interest to paleontology. Why are there no dinosaurs roaming the earth today? The answer appears to be that they were wiped out in a dramatic event, perhaps brought about as the result of a meteorite impact.

Numerous species have become extinct, typically as a result of their inability to adapt to changes in their natural environment. More recently, some extinctions or endangerments of species have been attributed to human activities, including hunting and the disruption of natural habitats. For the most part, however, extinction is simply a part of Earth's history, a result of the fact that nature has a way of destroying organisms that do not adapt (the "survival of the fittest"). But there have been occasions in the course of the planet's past in which vast numbers of individuals and species perished at once. A natural catastrophe may destroy a large population of individuals within a locality, a phenomenon known as mass mortality. Or mass mortality may take place on a global scale, destroying many species, in which case it is known as mass extinction.

CAUSES OF MASS EXTINCTION. The Bible depicts an example of near mass extinction, in the form of Noah's flood, and, indeed, several instances of mass extinction have resulted from sudden and dramatic changes in ocean levels. Others have been caused by tectonic events, most notably vast volcanic eruptions that filled the atmosphere with so much dust that they caused a violent change in temperature. Scientific speculation concerning other such extinctions has pointed to events in or from space—either the explosion of a star or the impact of a meteorite on Earth—as the cause of atmospheric changes and hence mass extinction.

Even though scientists have a reasonable idea of the immediate causes of mass extinction in some cases, their understanding of the ultimate or root causes is still limited. This fact was expressed by the University of Chicago paleobiologist David M. Raup, who wrote: "The disturbing reality is that for none of the thousands of well-documented extinctions in the geologic past do we have a solid explanation of why the extinction occurred."

EXAMPLES OF MASS EXTINCTION. The five largest known mass extinctions occurred at intervals of 50 Ma to 100 Ma over a span of time from about 435 to 65 million years ago. Most occurred at the end of a period, which is no accident, since geologists have used mass extinction as a factor in determining the parameters of a specific period.

In the late Ordovician period, about 435 Ma ago, a drop in the ocean level wiped out one-fourth of all marine families. Similarly, changes in sea level, along with climate changes, appear to have caused the destruction of one-fifth of existing marine families during the late Devonian period (about 357 Ma ago). Worst of all was the "great dying," as the extinction at the end of the Permian period (about 250 Ma) is known. Perhaps caused by a volcanic eruption in Siberia, it eliminated a staggering 96% of all species over a period of about a million years.

During the late Triassic period, about 198 million years ago, another catastrophe eliminated a quarter of marine families. Paleontologists know this, as they know about other mass extinctions, by the inordinate numbers of fossilized samples found in rock strata dating to that period. This reliance on the fossil record is also reflected in the fact that the scope of early mass extinctions usually is expressed in terms of marine life. As we have seen, the ocean environment provides the most reliable fossil record. Creatures died on land as well, but the terrestrial record is simply less reliable or less complete.

Scientific disagreement over the late-Triassic mass extinction exemplifies the fact that our knowledge of these distant events is not firmly established, but rather is subject to much scientific conjecture and dispute. (This does not mean that just any old idea can compete on an equal

KEY TERMS

ABSOLUTE AGE: The absolute age of a geologic phenomenon is its age in Earth years. Compare with *relative age.*

ATMOSPHERE: In general, an atmosphere is a blanket of gases surrounding a planet. Unless otherwise identified, however, the term refers to the atmosphere of Earth, which consists of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon, which together comprise 0.07%.

BIOSPHERE: A combination of all living things on Earth—plants, mammals, birds, reptiles, amphibians, aquatic life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

BIOSTRATIGRAPHY: An area of stratigraphy involving the study of fossilized plants and animals to establish dates for and correlations between stratigraphic layers.

CHRONOSTRATIGRAPHY: A subdiscipline of stratigraphy devoted to studying the relative ages of rocks. Compare with *geochronometry.*

CONTINENTAL DRIFT: The theory that the configuration of Earth's continents was once different than it is today; that some of the individual landmasses of today once were joined in other continental forms; and that these landmasses later separated and moved to their present locations.

CORRELATION: A method of establishing age relationships between various rock strata. There are two basic types of correlation: physical correlation, which requires comparison of the physical characteristics of the strata, and fossil correlation, the comparison of fossil types.

DATING: Any effort directed toward finding the age of a particular item or phenomenon. Methods of geologic dating are either relative (i.e., comparative and usually based on rock strata) or absolute. The latter, based on such methods as the study of radioactive isotopes, typically is given in terms of actual years or millions of years.

EON: The longest phase of geologic time. Earth's history has consisted of four eons, the Hadean or Priscoan, Archaean, Proterozoic, and Phanerozoic. The next-smallest subdivision of geologic time is the era.

EPOCH: The fourth-longest phase of geologic time, shorter than an era and longer than an age or a chron. The current epoch is the Holocene, which began about 0.01 Ma (10,000 years) ago.

ERA: The second-longest phase of geologic time, after an eon. The current eon, the Phanerozoic, has had three eras, the Paleozoic, Mesozoic, and Cenozoic, which is the current era. The next-smallest subdivision of geologic time is the period.

FOSSIL: The mineralized remains of any prehistoric life-form, especially those preserved in rock before the end of the last ice age.

FOSSILIZATION: The process by which a once-living organism becomes a fossil. Generally, fossilization involves mineralization of the organism's hard portions, such as bones, teeth, and shells.

KEY TERMS CONTINUED

GA: An abbreviation meaning "gigayears," or "billion years." The age of Earth is about 4.6 Ga.

GEOCHRONOMETRY: An area of stratigraphy devoted to determining absolute dates and time intervals. Compare with *chronostratigraphy.*

GEOLOGIC TIME: The vast stretch of time over which Earth's geologic development has occurred. This span (about 4.6 billion years) dwarfs the history of human existence, which is only about two million years. Much smaller still is the span of human civilization, only about 5,500 years.

HISTORICAL GEOLOGY: The study of Earth's physical history. Historical geology is one of two principal branches of geology, the other being physical geology.

INVERTEBRATE: An animal without an internal skeleton.

ISOTOPES: Atoms that have an equal number of protons, and hence are of the same element, but differ in their number of neutrons. This results in a difference of mass. An isotope may be either stable or radioactive.

LAW OF FAUNAL SUCCESSION: The principle that all samples of any given fossil species were deposited on Earth, regardless of location, at more or less the same time. This makes it possible to correlate widely separated strata.

MA: An abbreviation used by earth scientists, meaning "million years," or "megayears." When an event is designated as, for instance, 160 Ma, it usually means 160 million years ago.

MASS EXTINCTION: A phenomenon in which numerous species cease to exist at or around the same time, usually as the result of a natural calamity.

MINERALIZATION: A series of changes experienced by a once-living organism during fossilization. In mineralization, minerals in the organism are either replaced or augmented by different minerals, or the hard portions of the organism dissolve completely.

ORGANIC: At one time, chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals), and oxides, such as carbon dioxide.

PALEOBOTANY: An area of paleontology involving the study of past plant life.

PALEOECOLOGY: An area of paleontology devoted to studying the relationship between prehistoric plants and animals and their environments.

PALEONTOLOGY: The study of lifeforms from the distant past, primarily as revealed through the fossilized remains of plants and animals.

PALEOZOOLOGY: An area of paleontology devoted to the study of prehistoric animal life.

PERIOD: The third-longest phase of geologic time, after an era. The current eon, the Phanerozoic, has had 11 periods, and the current era, the Cenozoic, has consisted of three periods, of which the most recent is the Quaternary. The next-smallest subdivision of geologic time is the epoch.

KEY TERMS CONTINUED

PRECAMBRIAN TIME: A term that refers to the first three of four eons in Earth's history, which lasted from about 4,560 to about 545 Ma ago.

RADIOACTIVITY: A term describing a phenomenon whereby certain materials are subject to a form of decay brought about by the emission of high-energy particles or radiation. Forms of particles or energy include alpha particles (positively charged helium nuclei), beta particles (either electrons or subatomic particles called positrons, or gamma rays, which occupy the highest energy level in the electromagnetic spectrum.

RADIOMETRIC DATING: A method of absolute dating using ratios between "parent" isotopes and "daughter" isotopes, which are formed by the radioactive decay of parent isotopes. Radiometric dating also may involve ratios between radioactive isotopes and stable isotopes.

RELATIVE AGE: The relative age of a geologic phenomenon is its age compared with other geologic phenomena, particularly the stratigraphic record of rock layers. Compare with *absolute age.*

SEDIMENT: Material deposited at or near Earth's surface from a number of sources, most notably preexisting rock.

SEDIMENTARY ROCK: Rock formed by compression and deposition (i.e., formation of deposits) on the part of other rock and mineral particles. Sedimentary rock is one of the three major types of rock, along with igneous and metamorphic.

SEDIMENTOLOGY: The study and interpretation of sediments, including sedimentary processes and formations.

STRATA: Layers, or beds, of rocks beneath Earth's surface. The singular form is *stratum.*

STRATIGRAPHY: The study of rock layers, or strata, beneath Earth's surface.

VERTEBRATE: An animal with an internal skeleton.

footing: we are talking here about differences of opinion among highly trained specialists.) At any rate, some scientists refer to the late-Triassic mass extinction as being one of the less exciting or eventful mass extinctions. Of course, it is hard to see how a mass extinction could be unexciting or uneventful, but they mean this in comparative terms; on the other hand, some paleontologists maintain that the late-Triassic was among the most devastating.

As to the cause, some theorists point to a group of impact sites spread across Canada, the northern United States, and Ukraine, places that would have been more or less contiguous at the time of the mass extinction. Difficulties in analyzing the "signatures" left by the projectiles that made these impressions have prevented theorists from saying with any degree of certainty whether it was a comet or an asteroid that caused the impact. Others, in particular a team from the University of California at Berkeley led by geologist Paul R. Renne, cite a volcanic eruption as either the cause of the mass extinction, or at least a major abetting factor to an extinction already in progress. According to Renne and his team, basalt outcroppings scattered from New Jersey to Brazil to west Africa (again, areas that would have been contiguous then) suggest that a volcanic eruption of almost inconceivable magnitude occurred about 200 million years ago. Such an eruption would surely have destroyed vast quantities of living things.

The last and best known mass extinction occurred about 65 million years ago, marking the

end of the Cretaceous period—and the end of the dinosaurs. As to what happened, paleontologists and other scientists have proposed a number of theories: a rapid climate change; the emergence of new poisonous botanical species, eaten by herbivorous dinosaurs, that resulted in the passing of toxins along the food web (see Ecosystems); an inability to compete successfully with the rapidly evolving mammals; and even an epidemic disease to which the dinosaurs possessed no immunity.

Interesting as many of these theories are, none has gained anything like the widespread acceptance achieved by another scenario. According to this highly credible theory, an asteroid hit Earth, hurtling vast quantities of debris into the atmosphere, blocking out the sunlight, and greatly lowering Earth's surface temperature. Around the world, geologists have found traces of iridium deposited at a layer equivalent to the boundary between the Cretaceous and Tertiary periods, the Tertiary being the beginning of the present Cenozoic era. This is significant, because iridium seldom appears on Earth's surface—but it *is* found in asteroids.

HUMANS AND MASS EXTINCTION. There have been much more recent, if less dramatic, examples of mass extinction, including those caused by the most highly developed of all life-forms: humans. Among these examples are the well-documented (and *very* recent) mass extinctions brought on by destruction of tropical rainforests. Such activities are killing off a vast array of organisms: according to the highly respected Harvard biologist Edward O. Wilson, some 17,500 species are disappearing each year. But cases of mass extinction are not limited to modern times.

When prehistoric hunters (the ancestors of today's Native Americans) crossed the Bering land bridge from Siberia to Alaska some 12,000 years ago, they found an array of species unknown in the Americas today. These species included mammoths and mastodons; giant bears, beaver, and bison; and even saber-toothed tigers, camels, and lions. Perhaps most remarkable of all, it appears that prehistoric America was once home to a creature that would prove to be of enormous benefit to humans until the beginning of the automotive age: the horse. Horses did not reappear in the Americas until Europeans arrived to conquer those lands after A.D. 1500.

Were Dinosaurs Warm-Blooded?

One of the most significant scientific debates of the later twentieth and early twenty-first centuries, not only in paleontology but in the earth sciences or even science itself, is the question of whether or not the dinosaurs were warm-blooded. In other words, were they like modern reptiles, which must adjust their temperature by moving into the sunlight when they are cold, and into the shade when they are too hot? Or were they more like modern birds and mammals, whose bodies generate their own heat?

A warm-blooded animal always has a more or less constant body temperature, regardless of the temperature of its environment. This is due to the fact that it produces heat by the burning of food, as well as by physical activity, and stores that heat under a layer of fat just beneath the skin. Warm-blooded animals are also capable of cooling down their bodies by perspiring and panting. Birds and mammals are the only warm-blooded animals; all others are cold-blooded. A cold-blooded creature, on the other hand, lacks control over its body temperature and therefore is warm when its environment is warm, and cold when its environment is cold.

The difference between warm- and cold-blooded animals is partly one of metabolic rate, or the rate at which nutrients are broken down and converted into energy. Cold-blooded creatures have slow metabolic rates; think of a python that swallows a medium-sized mammal whole and takes several days to digest it. The dinosaur debate is therefore often framed as a question of whether the dinosaurs' bodies had a relatively high or relatively low metabolic rate.

THE DEBATE. Until the 1960s, there was no debate: dinosaurs, whose existence had been known for about a century, were assumed to be big, dumb, slow, cold-blooded creatures. Then, in 1968, Robert T. Bakker—an undergraduate at Yale University, not a professor or a full-fledged paleontologist—revolutionized the world of paleontology with a paper called "The Superiority of Dinosaurs."

In his article, Bakker described dinosaurs as "fast, agile, energetic creatures" whose physiology was so advanced that even the biggest and

heaviest of them could outrun a human. Just a year later, John H. Ostrom, a professor of paleontology who also happened to be at Yale, wrote that a recently identified species of theropod dinosaur must have been "an active and very agile predator."

Thus began the great dinosaur debate, which rages even today. *Jurassic Park* reinforced the Bakker-Ostrom position, portraying *Velociraptor* as a cunning, fast-moving predator with clear links to birds. And indeed there are many arguments for endothermy (warm-bloodedness) in dinosaurs—arguments that relate to everything from brain size to rate of growth to the latitudes at which dinosaur fossils have been located. On the other hand, there is plenty of evidence for ectothermy (cold-bloodedness), based on the dinosaurs' size, scaliness, the climate in the Mesozoic era, and so on.

To explore, compare, and judge these many arguments, the reader is encouraged to consult the "Were Dinosaurs Warm-Blooded?" Web site listed in the "Where to Learn More" section at the conclusion of this essay. However, a word of warning, as noted on that site: "The issue is a tangled, complex one. There are not just two sides to the issue; there are numerous competing hypotheses. If you're looking for a major controversy in science, look no further!"

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MINERALS

CONCEPT

A mineral is a naturally occurring, typically inorganic substance with a specific chemical composition and structure. An unknown mineral usually can be identified according to known characteristics of specific minerals in terms of certain parameters that include its appearance, its hardness, and the ways it breaks apart when fractured. Minerals are not to be confused with rocks, which are typically aggregates of minerals. There are some 3,700 varieties of mineral, a handful of which are abundant and wide-ranging in their application. Many more occur less frequently but are extremely important within a more limited field of uses.

HOW IT WORKS

Introduction to Minerals

The particulars of the mineral definition deserve some expansion, especially inasmuch as mineral has an everyday definition somewhat broader than its scientific definition. In everyday usage, minerals would be the natural, nonliving materials that make up rocks and are mined from the earth. According to this definition, minerals would include all metals, gemstones, clays, and ores. The scientific definition, on the other hand, is much narrower, as we shall see.

The fact that a mineral must be inorganic brings up another term that has a broader meaning in everyday life than in the world of science. At one time, the scientific definition of organic was more or less like the meaning assigned to it by nonscientists today, as describing all living or formerly living things, their parts, and substances that come from them. Today, however, chemists use the word organic to refer to any compound that contains carbon bonded to hydrogen, thus excluding carbonates (which are a type of mineral) and oxides such as carbon dioxide or carbon monoxide. Because a mineral must be inorganic, this definition eliminates coal and peat, both of which come from a wide-ranging group of organic substances known as hydrocarbons.

A mineral also occurs naturally, meaning that even though there are artificial substances that might be described as "mineral-like," they are not minerals. In this sense, the definition of a mineral is even more restricted than that of an element, discussed later in this essay, even though there are nearly 4,000 minerals and more than 92 elements. The number 92, of course, is not arbitrary: that is the number of elements that occur in nature. But there are additional elements, numbering 20 at the end of the twentieth century, that have been created artificially.

PHYSICAL AND CHEMICAL PROPERTIES OF MINERALS. The specific characteristics of minerals can be discussed both in physical and in chemical terms. From the standpoint of physics, which is concerned with matter, energy, and the interactions between the two, minerals would be described as crystalline solids. The definition of a mineral is narrowed further in terms of its chemistry, or its atomic characteristics, since a mineral must be of unvarying composition.

A mineral, then, must be solid under ordinary conditions of pressure and temperature. This excludes petroleum, for instance (which, in any case, would have been disqualified owing to its organic origins), as well as all other liquids

and gases. Moreover, a mineral cannot be just any type of solid but must be a crystalline one—that is, a solid in which the constituent parts have a simple and definite geometric arrangement that is repeated in all directions. This rule, for instance, eliminates clay, an example of an amorphous solid.

Chemically, a mineral must be of unvarying composition, a stipulation that effectively limits minerals to elements and compounds. Neither sand nor glass, for instance, is a mineral, because the composition of both can vary. Another way of putting this is to say that all minerals must have a definite chemical formula, which is not true of sand, dirt, glass, or any other mixture. Let us now look a bit more deeply into the nature of elements and compounds, which are collectively known as pure substances, so as to understand the minerals that are a subset of this larger grouping.

Elements

The periodic table of elements is a chart that appears in most classrooms where any of the physical sciences are taught. It lists all elements in order of atomic number, or the number of protons (positively charged subatomic particles) in the atomic nucleus. The highest atomic number of any naturally occurring element is 92, for uranium, though it should be noted that a very few elements with an atomic number lower than 92 have never actually been found on Earth. On the other hand, *all* elements with an atomic number higher than 92 are artificial, created either in laboratories or as the result of atomic testing.

An element is a substance made of only one type of atom, meaning that it cannot be broken down chemically to create a simpler substance. In the sense that each is a fundamental building block in the chemistry of the universe, all elements are, as it were, "created equal." They are not equal, however, in terms of their abundance. The first two elements on the periodic table, hydrogen and helium, represent 99.9% of the matter in the entire universe. Though Earth contains little of either, our planet is only a tiny dot within the vastness of space; by contrast, stars such as our Sun are composed almost entirely of those elements (see Sun, Moon, and Earth).

Abundance on earth. Of all elements, oxygen is by far the most plentiful on Earth, representing nearly half—49.2%—of the total mass of atoms found on this planet. (Here the term mass refers to the known elemental mass of the planet's atmosphere, waters, and crust; below the crust, scientists can only speculate, though it is likely that much of Earth's interior consists of iron.)

Together with silicon (25.7%), oxygen accounts for almost exactly three-fourths of the elemental mass of Earth. If we add in aluminum (7.5%), iron (4.71%), calcium (3.39%), sodium (2.63%), potassium (2.4%), and magnesium (1.93%), these eight elements make up about 97.46% of Earth's material. Hydrogen, so plentiful in the universe at large, ranks ninth on Earth, accounting for only 0.87% of the planet's known elemental mass. Nine other elements account for a total of 2% of Earth's composition: titanium (0.58%), chlorine (0.19%), phosphorus (0.11%), manganese (0.09%), carbon (0.08%), sulfur (0.06%), barium (0.04%), nitrogen (0.03%), and fluorine (0.03%). The remaining 0.49% is made up of various other elements.

Looking only at Earth's crust, the numbers change somewhat, especially at the lower end of the list. Listed below are the 12 most abundant elements in the planet's crust, known to earth scientists simply as "the abundant elements." These 12, which make up 99.23% of the known crustal mass, together form approximately 40 different minerals that account for the vast majority of that 99.23%. Following the name and chemical symbol of each element is the percentage of the crustal mass it composes.

Abundance of Elements in Earth's Crust

- Oxygen (O): 45.2%
- Silicon (Si): 27.2%
- Aluminum (Al): 8.0%
- Iron (Fe): 5.8%
- Calcium (Ca): 5.06%
- Magnesium (Mg): 2.77%
- Sodium (Na): 2.32%
- Potassium (K): 1.68%
- Titanium (Ti): 0.86%
- Hydrogen (H): 0.14%
- Manganese (Mn): 0.1%
- Phosphorus (P): 0.1%

Atoms, Molecules, and Bonding

As noted earlier, an element is identified by the number of protons in its nucleus, such that any atom with six protons *must* be carbon, since car-

bon has an atomic number of 6. The number of electrons, or negatively charged subatomic particles, is the same as the number of protons, giving an atom no net electric charge.

An atom may lose or gain electrons, however, in which case it becomes an ion, an atom or group of atoms with a net electric charge. An atom that has gained electrons, and thus has a negative charge, is called an anion. On the other hand, an atom that has lost electrons, thus becoming positive in charge, is a cation.

In addition to protons and electrons, an atom has neutrons, or neutrally charged particles, in its nucleus. Neutrons have a mass close to that of a proton, which is much larger than that of an electron, and thus the number of neutrons in an atom has a significant effect on its mass. Atoms that have the same number of protons (and therefore are of the same element), but differ in their number of neutrons, are called isotopes.

COMPOUNDS AND MIXTURES. Whereas there are only a very few elements, there are millions of compounds, or substances made of more than one atom. A simple example is water, formed by the bonding of two hydrogen atoms with one oxygen atom; hence the chemical formula for water, which is H_2O. Note that this is quite different from a mere mixture of hydrogen and oxygen, which would be something else entirely. Given the gaseous composition of the two elements, combined with the fact that both are extremely flammable, the result could hardly be more different from liquid water, which, of course, is used for putting out fires.

The difference between water and the hydrogen-oxygen mixture described is that whereas the latter is the result of mere physical mixing, water is created by chemical bonding. Chemical bonding is the joining, through electromagnetic attraction, of two or more atoms to create a compound. Of the three principal subatomic particles, only electrons are involved in chemical bonding—and only a small portion of those, known as valence electrons, which occupy the outer shell of an atom. Each element has a characteristic pattern of valence electrons, which determines the ways in which the atom bonds.

CHEMICAL BONDING. Noble gases, of which helium is an example, are noted for their lack of chemical reactivity, or their resistance to bonding. While studying these elements, the German chemist Richard Abegg (1869–1910) discovered that they all have eight valence electrons. His observation led to one of the most important principles of chemical bonding: atoms bond in such a way that they achieve the electron configuration of a noble gas. This concept, known as the octet rule, has been shown to be the case in most stable chemical compounds.

Abegg hypothesized that atoms combine with one another because they exchange electrons in such a way that both end up with eight valence electrons. This was an early model of ionic bonding, which results from attractions between ions with opposite electric charges: when they bond, these ions "complete" each other. Metals tend to form cations and bond with nonmetals that have formed anions. The bond between anions and cations is known as an ionic bond, and is extremely strong.

The other principal type of bond is a covalent bond. The result, once again, is eight valence electrons for each atom, but in this case, the nuclei of the two atoms share electrons. Neither atom "owns" them; rather, they share electrons. Today, chemists understand that most bonds are neither purely ionic nor purely covalent; instead, there is a wide range of hybrids between the two extremes, which are a function of the respective elements' electronegativity, or the relative ability of an atom to attract valence electrons. If one element has a much higher electronegativity value than the other one, the bond will be purely ionic, but if two elements have equal electronegativity values, the bond is purely covalent. Most bonds, however, fall somewhere between these two extremes.

INTERMOLECULAR BONDING. Chemical bonds exist between atoms and within a molecule. But there are also bonds *between* molecules, which affect the physical composition of a substance. The strength of intermolecular bonds is affected by the characteristics of the interatomic, or chemical, bond.

For example, the difference in electronegativity values between hydrogen and oxygen is great enough that the bond between them is not purely covalent, but instead is described as a polar covalent bond. Oxygen has a much higher electronegativity (3.5) than hydrogen (2.1), and therefore the electrons tend to gravitate toward the oxygen atom. As a result, water molecules have a strong negative charge on the side occu-

pied by the oxygen atom, with a resulting positive charge on the hydrogen side.

By contrast, molecules of petroleum, a combination of carbon and hydrogen, tend to be nonpolar, because carbon (with an electronegativity value of 2.5) and hydrogen have very similar electronegativity values. Therefore the electric charges are more or less evenly distributed in the molecule. As a result, water molecules form strong attractions, known as dipole-dipole attractions, to each other. Molecules of petroleum, on the other hand, have little attraction to each other, and the differences in charge distribution account for the fact that water and oil do not mix.

Even weaker than the bonds between nonpolar molecules, however, are those between highly reactive elements, such as the noble gases and the "noble metals"—gold, silver, and copper, which resist bonding with other elements. The type of intermolecular attraction that exists in such a situation is described by the term London dispersion forces, a reference to the German-born American physicist Fritz Wolfgang London (1900–1954).

The bonding between molecules of most other metals, however, is described by the electron sea model, which depicts metal atoms as floating in a "sea" of valence electrons. These valence electrons are highly mobile within the crystalline structure of the metal, and this mobility helps explain metals' high electric conductivity. The ease with which metal crystals allow themselves to be rearranged explains not only metals' ductility (their ability to be shaped) but also their ability to form alloys, a mixture containing two or more metals.

The Crystalline Structure of Minerals

By definition, a solid is a type of matter whose particles resist attempts at compression. Because of their close proximity, solid particles are fixed in an orderly and definite pattern. Within the larger category of solids are crystalline solids, or those in which the constituent parts are arranged in a simple, definite geometric pattern that is repeated in all directions.

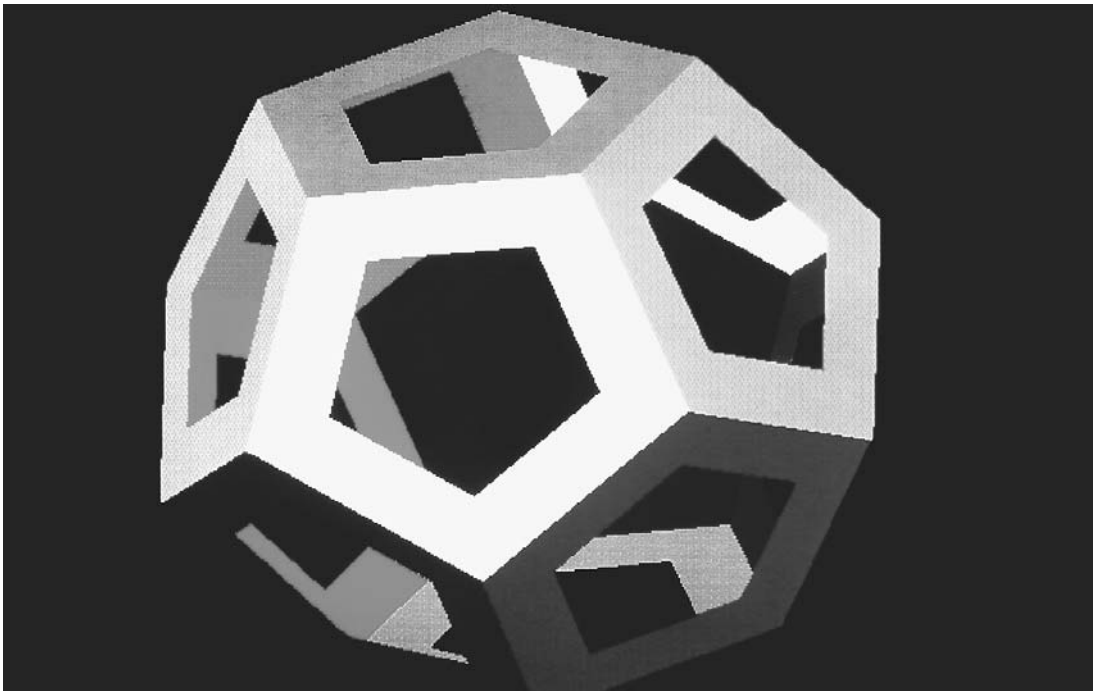
The term crystal is popularly associated with glass and with quartz, but only one of these is a crystalline solid. Quartz is a member of the silicates, a large group of minerals that we will discuss later in this essay. Glass, on the other hand, is an amorphous solid, meaning that its molecules are not arranged in an orderly pattern.

CRYSTAL SYSTEMS. Elsewhere in this book (Earth, Science, and Nonscience and Planetary Science), there is considerable discussion of misconceptions originating with Aristotle (384–322 B.C.). Despite his many achievements, including significant contributions to the biological sciences, the great Greek philosopher spawned a number of erroneous concepts, which prevailed in the physical sciences until the dawn of the modern era. At least Aristotle made an attempt at scientific study, however; for instance, he dissected dead animals to observe their anatomic structures. His teacher, Plato (427?–347 B.C.), on the other hand, is hardly ever placed among the ranks of those who contributed, even ever so slightly, to progress in the sciences.

There is a reason for this. Plato, in contrast to his pupil, made virtually no attempt to draw his ideas about the universe from an actual study of it. Within Plato's worldview, the specific qualities of any item, including those in the physical world, reflected the existence of perfect and pure ideas that were more "real" than the physical objects themselves. Typical of his philosophy was his idea of the five Platonic solids, or "perfect" geometric shapes that, he claimed, formed the atomic substructure of the world.

The "perfection" of the Platonic solids lay in the fact that they are the only five three-dimensional objects in which the faces constitute a single type of polygon (a closed shape with three or more sides, all straight), while the vertices (edges) are all alike. These five are the tetrahedron, octahedron, and icosahedron, composed of equilateral triangles (four, eight, and twenty, respectively); the cube, which, of course, is made of six squares; and the dodecahedron, made up of twelve pentagons. Plato associated the latter solid with the shape of atoms in outer space, while the other four corresponded to what the Greeks believed were the elements on Earth: fire (tetrahedron), earth (cube), air (octahedron), and water (icosahedron).

All of this, of course, is nonsense from the standpoint of science, though the Platonic solids are of interest within the realm of mathematics. Yet amazingly, Plato in his unscientific way actually touched on something close to the truth, as applied to the crystalline structure of minerals.



A dodecahedron, one of the Platonic solids. *(© Richard Duncan/Photo Researchers. Reproduced by permission.)*

Despite the large number of minerals, there are just six crystal systems, or geometric shapes formed by crystals. For any given mineral, it is possible for a crystallographer (a type of mineralogist concerned with the study of crystal structures) to identify its crystal system by studying a good, well-formed specimen, observing the faces of the crystal and the angles at which they meet.

An isometric crystal system is the most symmetrical of all, with faces and angles that are most clearly uniform. Because of differing types of polygon that make up the faces, as well as differing numbers of vertices, these crystals appear in 15 forms, several of which are almost eerily reminiscent of Plato's solids: not just the cube (exemplified by halite crystals) but also the octahedron (typical of spinels) and even the dodecahedron (garnets).

REAL-LIFE APPLICATIONS

Mineral Groups

Before the time of the great German mineralogist Georgius Agricola (1494–1555), attempts to classify minerals were almost entirely overshadowed by the mysticism of alchemy, by other nonscientific preoccupations, or by simple lack of knowledge. Agricola's *De re metallica* (On minerals, 1556), published after his death, constituted the first attempt at scientific mineralogy and mineral classification, but it would be two and a half centuries before the Swedish chemist Jöns Berzelius (1779–1848) developed the basics of the classification system used today.

Berzelius's classification system was refined later in the nineteenth century by the American mineralogist James Dwight Dana (1813–1895) and simplified by the American geologists Brian Mason (1917–) and L. G. Berry (1914–). In general terms, the classification system accepted by mineralogists today is as follows:

- Class 1: Native elements
- Class 2: Sulfides
- Class 3: Oxides and hydroxides
- Class 4: Halides
- Class 5: Carbonates, nitrates, borates, iodates
- Class 6: Sulfates, chromates, molybdates, tungstates
- Class 7: Phosphates, arsenates, vanadates
- Class 8: Silicates

NATIVE ELEMENTS. The first group, native elements, includes (among other

things) metallic elements that appear in pure form somewhere on Earth: aluminum, cadmium, chromium, copper, gold, indium, iron, lead, mercury, nickel, platinum, silver, tellurium, tin, titanium, and zinc. This may seem like a great number of elements, but it is only a small portion of the 87 metallic elements listed on the periodic table.

The native elements also include certain metallic alloys, a fact that might seem strange for several reasons. First of all, an alloy is a mixture, not a compound, and, second, people tend to think of alloys as being man-made, not natural. The list of metallic alloys included among the native elements, however, is very small, and they meet certain very specific mineralogic criteria regarding consistency of composition.

The native elements class also includes native nonmetals such as carbon, in the form of graphite or its considerably more valuable alter ego, diamond, as well as elemental silicon (an extremely important building block for minerals, as we shall see) and sulfur. For a full list of native elements and an explanation of criteria for inclusion, as well as similar data for the other classes of mineral, the reader is encouraged to consult the *Minerals by Name* Web site, the address of which is provided in "Where to Learn More" at the end of this essay.

SULFIDES AND HALIDES. Most important ores (a rock or mineral possessing economic value)—copper, lead, and silver—belong to the sulfides class, as does a mineral that often has been mistaken for a precious metal—iron sulfide, or pyrite. Better known by the colloquial term fool's gold, pyrite has proved valuable primarily to con artists who passed it off as the genuine article. During World War II, however, pyrite deposits near Ducktown, Tennessee, became valuable owing to the content of sulfur, which was extracted for use in defense applications.

Whereas the sulfides fit the common notion of a mineral as a hard substance, halides, which are typically soft and transparent, do not. Yet they are indeed a class of minerals, and they include one of the best-known minerals on Earth: halite, known chemically as NaCl or sodium chloride—or, in everyday language, table salt.

OXIDES. Oxides, as their name suggests, are minerals containing oxygen; however, if all oxygen-containing minerals were lumped into just one group, that group would take up almost the entire list. For instance, under the present system, silicates account for the vast majority of minerals, but since *those* contain oxygen as well, a list that grouped all oxygen-based minerals together would consist of only four classes: native elements, sulfides, halides, and a swollen oxide category that would include 90% of all known minerals.

Instead, the oxides class is limited only to noncomplex minerals that contain either oxygen or hydroxide (OH). Examples of oxides include magnetite (iron oxide) and corundum (aluminum oxide.) It should be pointed out that a single chemical name, such as iron oxide or aluminum oxide, is not limited to a single mineral; for example, anatase and brookite are both titanium oxide, but they represent different combinations.

OTHER NONSILICATES. All the mineral classes discussed to this point, as well as several others to follow, are called nonsilicates, a term that stresses the importance of silicates among mineral classes.

Like the oxides, the carbonates, or carbon-based minerals, are a varied group. This class also contains a large number of minerals, making it the most extensive group aside from silicates and phosphates. Among these are limestones and dolostones, some of the most abundant rocks on Earth.

The phosphates, despite their name, may or may not include phosphorus; in some cases, arsenic, vanadium, or antimony may appear in its place. The same is true of the sulfates, which may or may not involve sulfur; some include chromium, tungsten, selenium, tellurium, or molybdenum instead.

TWO QUESTIONABLE CLASSES. In addition to the seven formal classes just described, there are two other somewhat questionable classes of nonsilicate that might be included in a listing of minerals. They would be included, if at all, only with major reservations, since they do not strictly fit the fourfold definition of a mineral as crystalline in structure, natural, inorganic, and identifiable by a precise chemical formula. These two questionable groups are organics and mineraloids.

Organics, as their name suggests, have organic components, but as we have observed, "organic" is not the same as "biological." This

class excludes hard substances created in a biological setting—for example, bone or pearl—and includes only minerals that develop in a geologic setting yet have organic chemicals in their composition. By far the best-known example of this class, which includes only a half-dozen minerals, is amber, which is fossilized tree sap.

Amber is also among the mineraloids, which are not really "questionable" at all—they are clearly *not* minerals, since they do not have the necessary crystalline structure. Nevertheless, they often are listed among minerals in reference books and are likely to be sold by mineral dealers. The other four mineraloids include two other well-known substances, opal and obsidian.

SILICATES

Where minerals are concerned, the silicates are the "stars of the show": the most abundant and most widely used class of minerals. That being said, it should be pointed out that there are a handful of abundant nonsilicates, most notably the iron oxides hematite, magnetite, and goethite. A few other nonsilicates, while they are less abundant, are important to the makeup of Earth's crust, examples being the carbonates calcite and dolomite; the sulfides pyrite, sphalerite, galena, and chalcopyrite; and the sulfate gypsum. Yet the nonsilicates are not nearly as important as the class of minerals built around the element silicon.

Though it was discovered by Jöns Berzelius in 1823, owing to its abundance in the planet's minerals, silicon has been in use by humans for thousands of years. Indeed, silicon may have been one of the first elements formed in the Precambrian eons (see Geologic Time). Geologists believe that Earth once was composed primarily of molten iron, oxygen, silicon, and aluminum, which, of course, are still the predominant elements in the planet's crust. But because iron has a greater atomic mass, it settled toward the center, while the more lightweight elements rose to the surface. After oxygen, silicon is the most abundant of all elements on the planet, and compounds involving the two make up about 90% of the mass of Earth's crust.

SILICON, CARBON, AND OXYGEN. On the periodic table, silicon lies just below carbon, with which it shares an ability to form long strings of atoms. Because of this and other chemical characteristics, silicon, like carbon, is at the center of a vast array of compounds—organic in the case of carbon and inorganic in the case of silicon. Silicates, which, as noted earlier, account for nine-tenths of the mass of Earth's crust (and 30% of all minerals), are to silicon and mineralogy what hydrocarbons are to carbon and organic chemistry.

Whereas carbon forms it most important compounds with hydrogen—hydrocarbons such as petroleum—the most important silicon-containing compounds are those formed by bonds with oxygen. There is silica (SiO_2), for instance, commonly known as sand. Aside from its many applications on the beaches of the world, silica, when mixed with lime and soda (sodium carbonate) and other substances, makes glass. Like carbon, silicon has the ability to form polymers, or long, chainlike molecules. And whereas carbon polymers are built of hydrocarbons (plastics are an example), silicon polymers are made of silicon and oxygen in monomers, or strings of atoms, that form ribbons or sheets many millions of units long.

SILICATE SUBCLASSES. There are six subclasses of silicate, differentiated by structure. Nesosilicates include some the garnet group; gadolinite, which played a significant role in the isolation of the lanthanide series of elements during the nineteenth century; and zircon. The latter may seem to be associated with the cheap diamond simulant, or substitute, called cubic zirconium, or CZ. CZ, however, is an artificial "mineral," whereas zircon is the real thing—yet it, too, has been applied as a diamond simulant.

Just as silicon's close relative, carbon, can form sheets (this is the basic composition of graphite), so silicon can appear in sheets as the phyllosilicate subclass. Included among this group are minerals known for their softness: kaolinite, talc, and various types of mica. These are used in everything from countertops to talcum powder. The kaolinite derivative known as kaolin is applied, for instance, in the manufacture of porcelain, while some people in parts of Georgia, a state noted for its kaolinite deposits, claim that it can and should be chewed as an antacid stomach remedy. (One can even find little bags of kaolin sold for this purpose at convenience stores around Columbus in southern Georgia.)



Calcite with quartz. *(© Mark A. Schneider/Photo Researchers. Reproduced by permission.)*

Included in another subclass, the tectosilicates, are the feldspar and quartz groups, which are the two most abundant types of mineral in Earth's crust. Note that these are both groups: to a mineralogist, feldspar and quartz refer not to single minerals but to several within a larger grouping. Feldspar, whose name comes from the Swedish words for "field" and "mineral" (a reference to the fact that miners and farmers found the same rocks in their respective areas of labor), includes a number of varieties, such as albite (sodium aluminum silicate) or sanidine (potassium aluminum silicate).

Other, more obscure silicate subclasses include sorosilicates and inosilicates. Finally, there are cyclosilicates, such as beryl or beryllium aluminum silicate.

Identifying Minerals

Mineralogists identify unknown minerals by judging them in terms of various physical properties, including hardness, color and streak, luster, cleavage and fracture, density and specific gravity, and other factors, such as crystal form. Hardness, or the ability of one mineral to scratch another, may be measured against the Mohs scale, introduced in 1812 by the German mineralogist Friedrich Mohs (1773–1839). The scale rates minerals from 1 to 10, with 10 being equivalent to the hardness of a diamond and 1 that of talc, the softest mineral. (See Economic Geology for other scales, some of which are more applicable to specific types of minerals.)

Minerals sometimes can be identified by color, but this property can be so affected by the presence of impurities that mineralogists rely instead on streak. The latter term refers to the color of the powder produced when one mineral is scratched by another, harder one. Another visual property is luster, or the appearance of a mineral when light reflects off its surface. Among the terms used in identifying luster are metallic, vitreous (glassy), and dull.

The term cleavage refers to the way in which a mineral breaks—that is, the planes across which the mineral splits into pieces. For instance, muscovite tends to cleave only in one direction, forming thin sheets, while halite cleaves in three directions, which are all perpendicular to one another, forming cubes. The cleavage of a mineral reveals its crystal system; however, minerals are more likely to fracture (break along something other than a flat surface) than they are to cleave.

Density, specific gravity, and other properties. Density is the ratio of mass to volume, and specific grav-

ity is the ratio between the density of a particular substance and that of water. Specific gravity almost always is measured according to the metric system, because of the convenience: since the density of water is 1 g per cubic centimeter (g/cm^3), the specific gravity of a substance is identical to its density, except that specific gravity involves no units.

For example, gold has a density of 19.3 g/cm^3 and a specific gravity of 19.3. Its specific gravity, incidentally, is extremely high, and, indeed, one of the few metals that comes close is lead, which has a specific gravity of 11. By comparing specific gravity values and measuring the displacement of water when an object is set down in it, it is possible to determine whether an item purported to be gold actually is gold.

In addition to these more common parameters for identifying minerals, it may be possible to identify certain ones according to other specifics. There are minerals that exhibit fluorescent or phosphorescent characteristics, for instance. The first term refers to objects that glow when viewed under ultraviolet light, while the second term describes those that continue to glow after being exposed to visible light for a short period of time. Some minerals are magnetic, while others are radioactive.

NAMING MINERALS. Chemists long ago adopted a system for naming compounds so as to avoid the confusion of proliferating common names. The only compounds routinely referred to by their common names in the world of chemistry are water and ammonia; all others are known according to chemical nomenclature that is governed by specific rules. Thus, for instance, NaCl is never "salt," but "sodium chloride."

Geologists have not been able to develop such a consistent means of naming minerals. For one thing, as noted earlier, two minerals may be different from each other yet include the same elements. Furthermore, it is difficult (unlike the case of chemical compounds) to give minerals names that provide a great deal of information regarding their makeup. Instead, most minerals are simply named after people (usually scientists) or the locale in which they were found.

Abrasives

The physical properties of minerals, including many of the characteristics we have just discussed, have an enormous impact on their usefulness and commercial value. Some minerals, such as diamonds and corundum, are prized for their hardness, while others, ranging from marble to the "mineral" alabaster, are useful precisely because they are soft. Others, among them copper and gold, are not just soft but highly malleable, and this property makes them particularly useful in making products such as electrical wiring.

Diamonds, corundum, and other minerals valued for their hardness belong to a larger class of materials called abrasives. The latter includes sandpaper, which of course is made from one of the leading silicate derivatives, sand. Sandstone and quartz are abrasives, as are numerous variants of corundum, such as sapphire and garnets.

In 1891, American inventor Edward G. Acheson (1856–1931) created silicon carbide, later sold under the trade name Carborundum, by heating a mixture of clay and coke (almost pure carbon). For 50 years, Carborundum was the second-hardest substance known, diamonds being the hardest. Today other synthetic abrasives, made from aluminum oxide, boron carbide, and boron nitride, have supplanted Carborundum in importance.

Corundum, from the oxides class of mineral, can have numerous uses. Extremely hard, corundum, in the form of an unconsolidated rock commonly called emery, has been used as an abrasive since ancient times. Owing to its very high melting point—even higher than that of iron—corundum also is employed in making alumina, a fireproof product used in furnaces and fireplaces. Though pure corundum is colorless, when combined with trace amounts of certain elements, it can yield brilliant colors: hence, corundum with traces of chromium becomes a red ruby, while traces of iron, titanium, and other elements yield varieties of sapphire in yellow, green, and violet as well as the familiar blue.

This brings up an important point: many of the minerals named here are valued for much more than their abrasive qualities. Many of the 16 minerals used as gemstones, including corundum (source of both rubies and sapphires, as we have noted), garnet, quartz, and of course diamond, happen to be abrasives as well. (See Economic Geology for the full list of precious gems.)

DIAMONDS. Diamonds, in fact, are so greatly prized for their beauty and their application in jewelry that their role as "working" min-

erals—not just decorations—should be emphasized. The diamonds used in industry look quite different from the ones that appear in jewelry. Industrial diamonds are small, dark, and cloudy in appearance, and though they have the same chemical properties as gem-quality diamonds, they are cut with functionality (rather than beauty) in mind. A diamond is hard, but brittle: in other words, it can be broken, but it is very difficult to scratch or cut a diamond—except with another diamond.

On the other hand, the cutting of fine diamonds for jewelry is an art, exemplified in the alluring qualities of such famous gems as the jewels in the British Crown or the infamous Hope Diamond in Washington, D.C.'s Smithsonian Institution. Such diamonds—as well as the diamonds on an engagement ring—are cut to refract or bend light rays and to disperse the colors of visible light.

Soft and Ductile Minerals

At the other end of the Mohs scale are an array of minerals valued not for their hardness, but for opposite qualities. Calcite, for example, is often used in cleansers because, unlike an abrasive (also used for cleaning in some situations), it will not scratch a surface to which it is applied. Calcite takes another significant form, that of marble, which is used in sculpture, flooring, and ornamentation because of its softness and ease in carving—not to mention its great beauty.

Gypsum, used in plaster of paris and wallboard, is another soft mineral with applications in building. Though, obviously, soft minerals are not much value as structural materials, when stud walls of wood provide the structural stability for gypsum sheet wall coverings, the softness of the latter can be an advantage. Gypsum wallboard makes it easy to put in tacks or nails for pictures and other decorations, or to cut out a hole for a new door, yet it is plenty sturdy if bumped. Furthermore, it is much less expensive than most materials, such as wood paneling, that might be used to cover interior walls.

GOLD. Quite different sorts of minerals are valued not only for their softness but also their ductility or malleability. There is gold, for instance, the most ductile of all metals. A single troy ounce (31.1 g) can be hammered into a sheet just 0.00025 in. (0.00064 cm) thick, covering 68 sq. ft. (6.3 sq m), while a piece of gold weighing about as much as a raisin (0.0022 lb., or 1 g) can be pulled into the shape of a wire 1.5 mi. (2.4 km) long. This, along with its qualities as a conductor of heat and electricity, would give it a number of other applications, were it not for the high cost of gold.

Therefore, gold, if it were a person, would have to be content with being only the most prized and admired of all metallic minerals, an element for which men and whole armies have fought and sometimes died. Gold is one of the few metals that is not silver, gray, or white in appearance, and its beautifully distinctive color caught the eyes of metalsmiths and royalty from the beginning of civilization. Hence it was one of the first widely used metals.

Records from India dating back to 5000 B.C. suggest a familiarity with gold, and jewelry found in Egyptian tombs indicates the use of sophisticated techniques among the goldsmiths of Egypt as early as 2600 B.C. Likewise, the Bible mentions gold in several passages, and the Romans called it *aurum* ("shining dawn"), which explains its chemical symbol, Au.

COPPER. Copper, gold, and silver are together known as coinage metals. They have all been used for making coins, a reflection not only of their attractiveness and malleability, but also of their resistance to oxidation. (Oxygen has a highly corrosive influence on metals, causing rust, tarnishing, and other effects normally associated with aging but in fact resulting from the reaction of metal and oxygen.) Of the three coinage metals, copper is by far the most versatile, widely used for electrical wiring and in making cookware. Due to the high conductivity of copper, a heated copper pan has a uniform temperature, but copper pots must be coated with tin because too much copper in food is toxic.

Its resistance to corrosion makes copper ideal for plumbing. Likewise, its use in making coins resulted from its anticorrosive qualities, combined with its beauty. These qualities led to the use of copper in decorative applications for which gold would have been much too expensive: many old buildings used copper roofs, and the Statue of Liberty is covered in 300 thick copper plates. As for why the statue and many old copper roofs are green rather than copper-colored, the reason is that copper does eventually corrode when exposed to air for long periods of time. It develops a thin layer of black copper oxide, and

as the years pass, the reaction with carbon dioxide in the air leads to the formation of copper carbonate, which imparts a greenish color.

Unlike silver and gold, copper is still used as a coinage metal, though it, too, has been increasingly taken off the market for this purpose due to the high expense involved. Ironically, though most people think of pennies as containing copper, in fact the penny is the only American coin that contains *no* copper alloys. Because the amount of copper necessary to make a penny today costs more than one cent, a penny is actually made of zinc with a thin copper coating.

Insulation and Other Applications

Whereas copper is useful because it conducts heat and electricity well, other minerals (e.g., kyanite, andalusite, muscovite, and silimanite) are valuable for their ability *not* to conduct heat or electricity. Muscovite is often used for insulation in electrical devices, though its many qualities make it a mineral prized for a number of reasons.

Its cleavage and lustrous appearance, combined with its transparency and almost complete lack of color, made it useful for glass in the windowpanes of homes owned by noblemen and other wealthy Europeans of the Middle Ages. Today, muscovite is the material in furnace and stove doors: like ordinary glass, it makes it possible for one to look inside without opening the door, but unlike glass, it is an excellent insulator. The glass-like quality of muscovite also makes it a popular material in wallpaper, where ground muscovite provides a glassy sheen.

In the same vein, asbestos—which may be made of chrysotile, crocidolite, or other minerals—has been prized for a number of qualities, including its flexibility and fiber-like cleavage. These factors, combined with its great heat resistance and its resistance to flame, have made it useful for fireproofing applications, as for instance in roofing materials, insulation for heating and electrical devices, brake linings, and suits for firefighters and others who must work around flames and great heat. However, information linking asbestos and certain forms of cancer, which began to circulate in the 1970s, led to a sharp decline in the asbestos industry.

Minerals for health or otherwise. All sorts of other properties give minerals value. Halite, or table salt, is an important—perhaps too important!—part of the American diet. Nor is it the only consumable mineral; people also take minerals in dietary supplements, which is appropriate since the human body itself contains numerous minerals. In addition to a very high proportion of carbon, the body also contains a significant amount of iron, a critical component in red blood cells, as well as smaller amounts of minerals such as zinc. Additionally, there are trace minerals, so called because only traces of them are present in the body, that include cobalt, copper, manganese, molybdenum, nickel, selenium, silicon, and vanadium.

One mineral that does not belong in the human body is lead, which has been linked with a number of health risks. The human body can only excrete very small quantities of lead a day, and this is particularly true of children. Even in small concentrations, lead can cause elevation of blood pressure, and higher concentrations can effect the central nervous system, resulting in decreased mental functioning, hearing damage, coma, and possibly even death.

The ancient Romans, however, did not know this, and used what they called *plumbum* in making water pipes. (The Latin word is the root of our own term *plumber.*) Many historians believe that *plumbum* in the Romans' water supply was one of the reasons behind the decline and fall of the Roman Empire.

Even in the early twentieth century, people did not know about the hazards associated with lead, and therefore it was applied as an ingredient in paint. In addition, it was used in water pipes, and as an antiknock agent in gasolines. Increased awareness of the health hazards involved have led to a discontinuation of these practices.

Graphite. Pencil "lead," on the other hand, is actually a mixture of clay with graphite, a form of carbon that is also useful as a dry lubricant because of its unusual cleavage. It is slippery because it is actually a series of atomic sheets, rather like a big, thick stack of carbon paper: if the stack is heavy, the sheets are likely to slide against one another.

Actually, people born after about 1980 may have little experience with carbon paper, which was gradually phased out as photocopiers became cheaper and more readily available. Today, carbon paper is most often encountered

KEY TERMS

ALLOY: A mixture of two or more metals.

ANION: The negative ion that results when an atom or group of atoms gains one or more electrons.

ATOM: The smallest particle of an element, consisting of protons, neutrons, and electrons. An atom can exist either alone or in combination with other atoms in a molecule.

ATOMIC NUMBER: The number of protons in the nucleus of an atom. Since this number is different for each element, elements are listed on the periodic table in order of atomic number.

CATION: The positive ion that results when an atom or group of atoms loses one or more electrons.

CHEMICAL BONDING: The joining, through electromagnetic forces, of atoms representing different elements. The principal methods of combining are through covalent and ionic bonding, though few bonds are purely one or the other.

CLEAVAGE: A term referring to the characteristic patterns by which a mineral breaks and specifically to the planes across which breaking occurs.

COMPOUND: A substance made up of atoms of more than one element, chemically bonded to one another.

COVALENT BONDING: A type of chemical bonding in which two atoms share valence electrons.

CRUST: The uppermost division of the solid earth, representing less than 1% of its volume and varying in depth from 3 mi. to 37 mi. (5–60 km).

CRYSTALLINE SOLID: A type of solid in which the constituent parts have a simple and definite geometric arrangement that is repeated in all directions.

ELECTRON: A negatively charged particle in an atom, which spins around the nucleus.

ELECTRONEGATIVITY: The relative ability of an atom to attract valence electrons.

ELEMENT: A substance made up of only one kind of atom. Unlike compounds, elements cannot be broken chemically into other substances.

HARDNESS: In mineralogy, the ability of one mineral to scratch another. This is measured by the Mohs scale.

HYDROCARBON: Any chemical compound whose molecules are made up of nothing but carbon and hydrogen atoms.

ION: An atom or group of atoms that has lost or gained one or more electrons and thus has a net electric charge. Positively charged ions are called *cations,* and negatively charged ones are called *anions.*

IONIC BONDING: A form of chemical bonding that results from attractions between ions with opposite electric charges.

when signing a credit-card receipt: the signature goes through the graphite-based backing of the receipt onto a customer copy.

In such a situation, one might notice that the copied image of the signature looks as though it were signed in pencil, which of course is fitting

KEY TERMS CONTINUED

LUSTER: The appearance of a mineral when light reflects off its surface. Among the terms used in identifying luster are metallic, vitreous (glassy), and dull.

MINERAL: A naturally occurring, typically inorganic substance with a specific chemical composition and a crystalline structure. Unknown minerals usually can be identified in terms of specific parameters, such as hardness or luster.

MINERALOGY: The study of minerals, which includes a number of smaller subdisciplines, such as crystallography.

MIXTURE: A substance with a variable composition, meaning that it is composed of molecules or atoms of differing types and in variable proportions.

MOHS SCALE: A scale, introduced in 1812 by the German mineralogist Friedrich Mohs (1773–1839), that rates the hardness of minerals from 1 to 10. Ten is equivalent to the hardness of a diamond and 1 that of talc, an extremely soft mineral.

MONOMERS: Small, individual subunits that join together to form polymers.

NUCLEUS: The center of an atom, a region where protons and neutrons are located and around which electrons spin.

ORE: A rock or mineral possessing economic value.

ORGANIC: At one time, chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon and hydrogen, thus excluding carbonates (which are minerals) and oxides such as carbon dioxide.

PERIODIC TABLE OF ELEMENTS: A chart that shows the elements arranged in order of atomic number, along with the chemical symbol and the average atomic mass for that particular element.

POLYMERS: Large, typically chainlike molecules composed of numerous smaller, repeating units known as monomers.

PROTON: A positively charged particle in an atom.

PURE SUBSTANCE: A substance, whether an element or compound, that has the same chemical composition throughout. Compare with *mixture.*

REACTIVITY: A term referring to the ability of one element to bond with others. The higher the reactivity (and, hence, the electronegativity value), the greater the tendency to bond.

ROCK: An aggregate of minerals.

SPECIFIC GRAVITY: The ratio between the density of a particular substance and that of water.

STREAK: The color of the powder produced when one mineral is scratched by another, harder one.

VALENCE ELECTRONS: Electrons that occupy the highest principal energy level in an atom. These are the electrons involved in chemical bonding.

due to the application of graphite in pencil "lead." In ancient times, people did indeed use lead—which is part of the "carbon family" of elements, along with carbon and silicon—for writing, because it left gray marks on a surface. Even today, people still use the word "lead" in refer-

ence to pencils, much as they still refer to a galvanized steel roof with a zinc coating as a "tin roof."

(For more about minerals, see Rocks. The economic applications of both minerals and rocks are discussed in Economic Geology. In addition, Paleontology contains a discussion of fossilization, a process in which minerals eventually replace organic material in long-dead organisms.)

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ROCKS

CONCEPT

It might come as a surprise to learn that geologists regularly use an unscientific-sounding term, rocks. Yet as is almost always the case with a word used both in everyday language and within the realm of a scientific discipline, the meanings are not the same. For one thing, *rock* and *stone* are not interchangeable, as they are in ordinary discussion. The second of these two terms is used only occasionally, primarily as a suffix in the names of various rocks, such as limestone or sandstone. On the other hand, a rock is an aggregate of minerals or organic material. Rocks are of three different types: igneous, formed by crystallization of molten minerals, as in a volcano; sedimentary, usually formed by deposition, compaction, or cementation of weathered rock; and metamorphic, formed by alteration of preexisting rock.

HOW IT WORKS

An Introduction to Rocks

To expand somewhat on the definition of *rock,* the term may be said to describe an aggregate of minerals or organic material, which may or may not appear in consolidated form. Consolidation, which we will explore further within the context of sedimentary rock, is a process whereby materials become compacted, or experience an increase in density. It is likely that the image that comes to mind when the word rock is mentioned is that of a consolidated one, but it is important to remember that the term also can apply to loose particles.

The role of organic material in forming rocks also belongs primarily within the context of sedimentary, as opposed to igneous or metamorphic, rocks. There are, indeed, a handful of rocks that include organic material, an example being coal, but the vast majority are purely inorganic in origin. The inorganic materials that make up rocks are minerals, discussed in the next section. Rocks and minerals of economic value are called ores, which are examined in greater depth elsewhere, within the context of Economic Geology.

Minerals Defined

The definition of a mineral includes four components: it must appear in nature and therefore not be artificial, it must be inorganic in origin, it must have a definite chemical composition, and it must have a crystalline internal structure. The first of these stipulations clearly indicates that there is no such thing as a man-made mineral; as for the other three parts of the definition, they deserve a bit of clarification.

At one time, the term *organic,* even within the realm of chemistry, referred to all living or formerly living things, their parts, and substances that come from them. Today, however, chemists use the word to describe any compound that contains carbon and hydrogen, thus excluding carbonates (which are a type of mineral) and oxides such as carbon dioxide or carbon monoxide.

NONVARYING COMPOSITION. The third stipulation, that a mineral must be of nonvarying composition, limits minerals almost exclusively to elements and compounds—that is, either to substances that cannot be chemically

broken down to yield simpler substances or to substances formed by the chemical bonding of elements. The chemical bonding of elements is a process quite different from mixing, and a compound is not to be confused with a mixture, whose composition is highly variable.

Another way of putting this is to say that all minerals must have a definite chemical formula, which is not possible with a mixture such as dirt or glass. The Minerals essay, which the reader is encouraged to consult for further information, makes reference to certain alloys, or mixtures of metals, that are classified as minerals. These alloys, however, are exceptional and fit certain specific characteristics of interest to mineralogists. The vast majority of the more than 3,700 known varieties of mineral constitute either a single element or a single compound.

CRYSTALLINE STRUCTURE. The fact that a mineral must have a crystalline structure implies that it must be a solid, since all crystalline substances are solids. A solid, of course, is a type of matter whose particles, in contrast to those of a gas or liquid, maintain an orderly and definite arrangement and resist attempts at compression. Thus, petroleum cannot be a mineral, nor is "mineral spirits," a liquid paint thinner made from petroleum (and further disqualified by the fact that it is artificial in origin).

Crystalline solids are those in which the constituent parts are arranged in a simple, definite geometric pattern that is repeated in all directions. These solids are contrasted with amorphous solids, such as clay. Metals are crystalline in structure; indeed, several metallic elements that appear on Earth in pure form (for example, gold, copper, and silver) also are classified as minerals.

Identifying Minerals

The type of crystal that appears in a mineral is one of several characteristics that make it possible for a mineralogist to identify an unidentified mineral. Although, as noted earlier, there are nearly 4,000 known varieties of mineral, there are just six crystal systems, or geometric shapes formed by crystals. Crystallographers, or mineralogists concerned with the study of crystal structures, are able to identify the crystal system by studying a good, well-formed specimen of a mineral, observing the faces of the crystal and the angles at which they meet.

Other characteristics by which minerals can be studied and identified visually are color, streak, and luster. The first of these features is not particularly reliable, because impurities in the mineral may greatly affect its hue. Therefore, mineralogists are much more likely to rely on streak, or the color of the powder produced when one mineral is scratched by a harder one. Luster, the appearance of a mineral when light reflects off its surface, is described by such terms as vitreous (glassy), dull, or metallic.

HARDNESS. Minerals also can be identified according to what might be called tactile properties, or characteristics best discerned through the sense of touch. One of the most important among such properties is hardness, defined as the ability of one mineral to scratch another. Hardness is measured by the Mohs scale, introduced in 1812 by the German mineralogist Friedrich Mohs (1773–1839).

The scale rates minerals from 1 to 10, with 1 being equivalent to the hardness of talc, a mineral so soft that it is used for making talcum powder. A 2 on the Mohs scale is the hardness of gypsum, which is still so soft that it can be scratched by a human fingernail. Above a 5 on the scale, roughly equal to the hardness of a pocketknife or glass, are potassium feldspar (6), quartz (7), topaz (8), corundum (9), and diamond (10).

OTHER PROPERTIES. Other tactile parameters are cleavage, the planes across which the mineral breaks, and fracture, the tendency to break along something other than a flat surface. Minerals also can be evaluated by their density (ratio of mass to volume) or specific gravity (ratio between the mineral's density and that of water). Density and specific-gravity measures are particularly important for extremely dense materials, such as lead or gold.

In addition to these specifics, others may be used for identifying some kinds of minerals. Magnetite and a few other minerals, for instance, are magnetic, while minerals containing uranium and other elements with a high atomic number may be radioactive, or subject to the spontaneous emission of high-energy particles. Still others are fluorescent, meaning that they glow when viewed under ultraviolet light, or phosphorescent, meaning that they continue to glow after

being exposed to visible light for a short period of time.

Mineral Groups

Minerals are classified into eight basic groups:

- Class 1: Native elements
- Class 2: Sulfides
- Class 3: Oxides and hydroxides
- Class 4: Halides
- Class 5: Carbonates, nitrates, borates, iodates
- Class 6: Sulfates, chromates, molybdates, tungstates
- Class 7: Phosphates, arsenates, vanadates
- Class 8: Silicates

The first group, native elements, includes metallic elements that appear in pure form somewhere on Earth; certain metallic alloys, alluded to earlier; and native nonmetals, semimetals, and minerals with metallic and nonmetallic elements. Sulfides include the most important ores of copper, lead, and silver, while halides are typically soft and transparent minerals containing at least one element from the halogens family: fluorine, chlorine, iodine, and bromine. (The most well known halide, table salt, is a good example of an unconsolidated mineral.)

Oxides are noncomplex minerals that contain either oxygen or hydroxide (OH). Included in the oxide class are such well-known materials as magnetite and corundum, widely used in industry. Other nonsilicates (a term that stresses the importance of silicates among mineral classes) include carbonates, or carbon-based minerals, as well as phosphates and sulfates. The latter are distinguished from sulfides by virtue of the fact that they include a complex anion (a negatively charged atom or group of atoms) in which an atom of sulfur, chromium, tungsten, selenium, tellurium, or molybdenum (or a combination of these) is attached to four oxygen atoms.

There are two other somewhat questionable classes of nonsilicate that might be included in a listing of minerals—organics and mineraloids. Though they have organic components, organics—for example, amber—originated in a geologic and not a biological setting. Mineraloids, among them, opal and obsidian, are not minerals because they lack the necessary crystalline structure, but they can be listed under the more loosely defined heading of "rocks."

silicates. Only a few abundant or important minerals are nonsilicates, for example, the iron oxides hematite, magnetite, and goethite; the carbonates calcite and dolomite; the sulfides pyrite, sphalerite, galena, and chalcopyrite; and the sulfate gypsum. The vast majority of minerals, including the most abundant ones, belong to a single class, that of silicates, which accounts for 30% of all minerals. As their name implies, they are built around the element silicon, which bonds to four oxygen atoms to form what are called silica tetrahedra.

Silicon, which lies just below carbon on the periodic table of elements, is noted, like carbon, for its ability to form long strings of atoms. Carbon-hydrogen formations, or hydrocarbons, are the foundation of organic chemistry, while formations of oxygen and silicon—the two most abundant elements on Earth—provide the basis for a vast array of geologic materials. There is silica, for instance, better known as sand, which consists of silicon bonded to two carbon atoms.

Then there are the silicates, which are grouped according to structure into six subclasses. Among these subclasses, discussed in the Minerals essay, are smaller groupings that include a number of well-known mineral types: garnet, zircon, kaolinite, talc, mica, and the two most abundant minerals on Earth, feldspar and quartz. The name *feldspar* comes from the Swedish words *feld* ("field") and *spar* ("mineral"), because Swedish miners tended to come across the same rocks that Swedish farmers found themselves extracting from their fields.

Real-Life Applications

Rocks and Human Existence

Rocks are all around us, especially in our building materials but also in everything from jewelry to chalk. Then, of course, there are the rocks that exist in nature, whether in our backyards or in some more dramatic setting, such as a national park or along a rugged coastline. Indeed, humans have a long history of involvement with rocks—a history that goes far back to the aptly named Stone Age.



Chichén-Itzá, a Mayan stone pyramid in the state of Yucatán, Mexico. *(© Ulrike Welsch/Photo Researchers. Reproduced by permission.)*

The latter term refers to a period in which the most sophisticated human tools were those made of rock—that is, before the development of the first important alloy used in making tools, bronze. The Bronze Age began in the Near East in about 3300 B.C. and lasted until about 1200 B.C., when the development of iron-making technology introduced still more advanced varieties of tools.

These dates apply to the Near East, specifically to such areas as Mesopotamia and Egypt, which took the lead in ancient technology, followed much later by China and the Indus Valley civilization of what is now Pakistan. The rest of the world was even slower in adopting the use of metal: for instance, the civilizations of the Americas did not enter the Bronze Age for almost 4,000 years, in about A.D. 1100. Nor did they ever develop iron tools before the arrival of the Europeans in about 1500.

THE STONE AGE. In any case, the Stone Age, which practically began with the species *Homo sapiens* itself, was unquestionably the longest of the three ages. The Stone Age is divided into two periods: Paleolithic and Neolithic, sometimes called Old and New Stone Age, respectively. (There was also a middle phase, called the Mesolithic, but this term is not used as widely as Paleolithic or Neolithic.) Throughout much of this time, humans lived in rock caves and used rock tools, including arrowheads for

killing animals and (relatively late in prehistory) flint for creating fire.

The Paleolithic, characterized by the use of crude tools chipped from pieces of stone, began sometime between 2.5 and 1.8 million years ago and lasted until last ice age ended (and the present Holocene epoch began), about 10,000 years ago. The Neolithic period that followed saw enormous advances in technology, so many advances that historians speak of a "Neolithic Revolution" that included the development of much more sophisticated, polished tools. The mining of gold, copper, and various other ores began long before the development of the first alloys (bronze is formed by the mixture of copper and tin). Yet even after humans discovered metals, they continued to use stone tools.

THE PYRAMIDS AND OTHER STONE STRUCTURES. Indeed, the great pyramids of Egypt, built during the period from about 2600-2400 B.C., were constructed primarily with the use of stone rather than metal tools. The structures themselves, of course, also reflect the tight connection between humans and rocks. Built of limestone, the pyramids are still standing some 4,500 years later, even as structures of clay and mud built at about the same time in Mesopotamia (a region poor in stone resources) have long since dwindled to dust.

Incidentally, the great pyramids once had surfaces of polished limestone, such that they gleamed in the desert sun. Centuries later, Arab invaders in the seventh century A.D. stripped this limestone facing to use it in other structures, and the only part of the facing that remains today is high atop the pyramid of Khafre. For this reason, Khafre's pyramid is slightly taller than the structure known as *the* Great Pyramid, that of Cheops, or Khufu, which was originally the largest pyramid.

The centuries that have followed the building of those great structures likewise are defined, at least in part, by their buildings of stone. The Bible is full of references to stones, whether those used in building Solomon's temple or the precious gemstones said to form the gates of the New Jerusalem described in the Book of Revelation. Greece and Rome, too, are known for their structures of stone, ranging from marble (limestone that has undergone metamorphism) to unconsolidated stones in early forms of concrete, pioneered by the Egyptians.

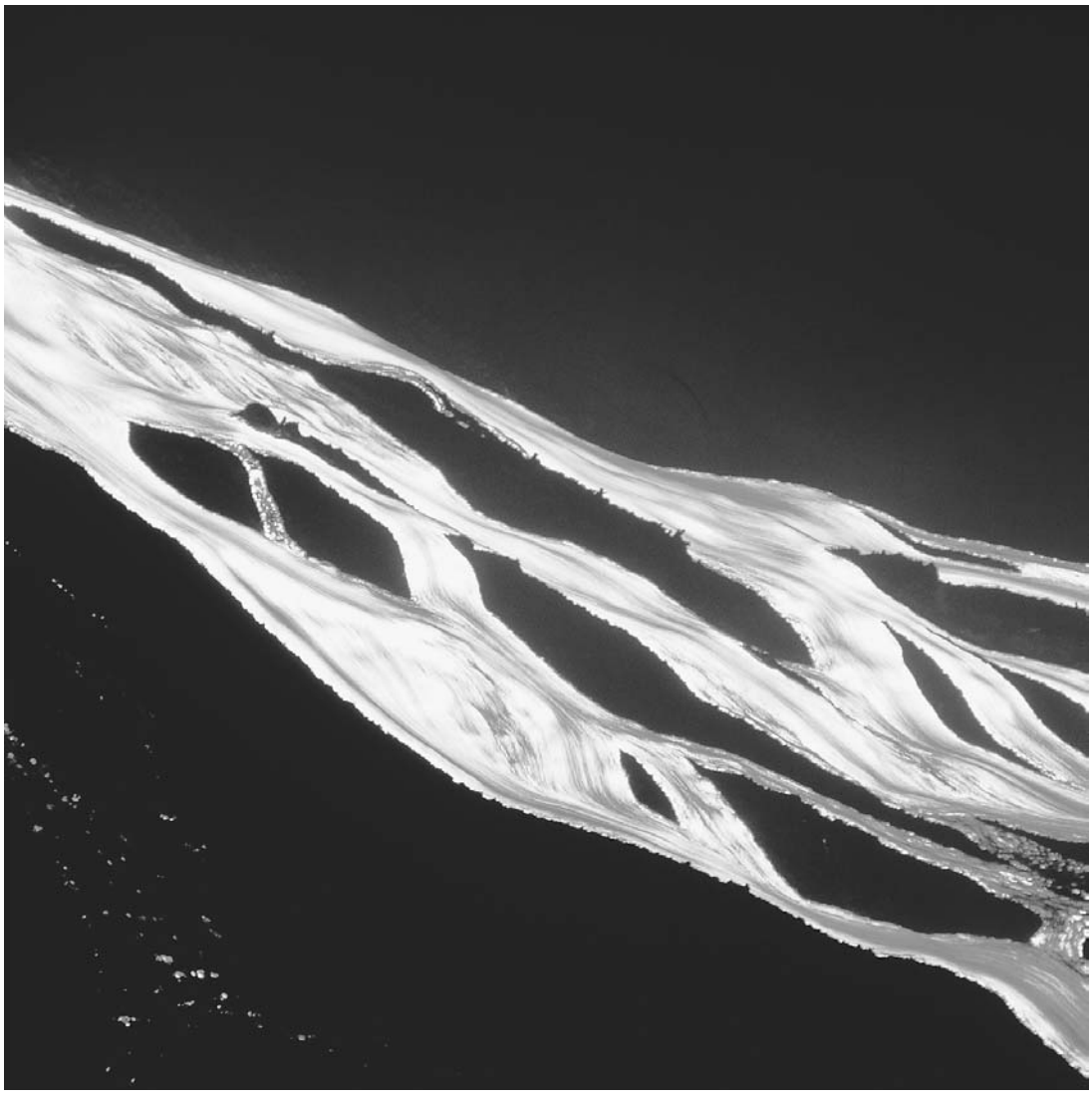
Still later, medieval Europe built its cathedrals and castles of stone, though it should be noted that the idea of the castle came from the Middle East, where the absence of lumber for fortresses caused Syrian castle builders to make use of abundant sandstone instead. Other societies left behind their own great stone monuments: the Great Wall of China, Angkor Wat in southeast Asia, the pyramids of Central America and Machu Picchu in South America, the great cliffside dwellings of what is now the southwestern United States, and the stone churches of medieval Ethiopia.

Certainly there were civilizations that created great structures of wood, but these structures were simply not as durable. The oldest wood building, a Buddhist temple at Horyuji in Japan, dates back only to A.D. 607, which, of course, is quite impressive for a wooden structure. But it hardly compares to what may well be the oldest known human structure, a windbreak discovered by the paleobiologist Mary Leakey (1913–1996) in Tanzania in 1960. Consisting of a group of lava blocks that form a rough circle, it is believed to be 1.75 million years old.

Mineralogy and Petrology

Not surprisingly, mineralogy is concerned with minerals—their physical properties, chemical makeup, crystalline structures, occurrence, distribution, and physical origins. Researchers whose work focuses on the physical origins of minerals study data and draw on the principles of physics and chemistry to develop hypotheses regarding the ways minerals form. Other mineralogical studies may involve the identification of a newly discovered mineral or the synthesis of mineral-like materials for industrial purposes.

The study of rocks is called petrology, from a Greek root meaning "rock." (Hence also the words *petroleum* and *petrify.*) Its areas of interest with regard to rocks are much the same as those of mineralogy as they relate to minerals: physical properties, distribution, and origins. It includes two major subdisciplines, experimental petrology, or the synthesis of rocks in a laboratory as a means of learning the conditions under which rocks are formed in the natural world, and petrography, or the study of rocks observed in thin sections through a petrographic microscope, which uses polarized light.



Lava flow after the 1992 eruption of Mount Etna in Sicily. When it cools, lava becomes igneous rock. *(© B. Edmaier/Photo Researchers. Reproduced by permission.)*

Owing to the fact that most rocks contain minerals, petrology draws on and overlaps with mineralogical studies to a great extent. At the same time, it goes beyond mineralogy, inasmuch as it is concerned with materials that contain organic substances, which are most likely to appear within the realm of sedimentary rock. Petrologists also are concerned with the other two principal types of rock, igneous and metamorphic.

Igneous Rocks

Igneous rock is rock formed by the crystallization of molten materials. It most commonly is associated with volcanoes, though, in fact, it comes into play in the context of numerous plate tectonic processes, such as seafloor spreading (see Plate Tectonics). The molten rock that becomes igneous rock is known as magma when it is below the surface of the earth and lava when it is at or near the earth's surface. Its most notable characteristic is its interlocking crystals. For the most part, igneous rocks do not have a layered texture.

When igneous rocks form deep within the Earth, they are likely to have large crystals, an indication of the fact that a longer period of time elapsed while the magma was cooling. On the other hand, volcanic rocks and others that form at or near Earth's surface are apt to have very small crystals. Obsidian (which, as we have noted, is not truly a mineral owing to its lack of

crystals) is formed when hot lava comes into contact with water; as a result, it cools so quickly that crystals never have time to develop. Sometimes called volcanic glass, it once was used by prehistoric peoples as a cutting tool.

Classifying and identifying igneous rocks. Igneous rocks can be classified in several ways, referring to the means by which they were formed, the size of their crystals, and their mineral content. Extrusive igneous rocks, ejected by volcanoes to crystallize at or near Earth's surface, have small crystals, whereas intrusive igneous rocks, which cooled slowly beneath the surface, have larger crystals. Sometimes the terms *plutonic* and *volcanic,* which roughly correspond to *intrusive* and *extrusive,* respectively, are used.

Igneous rocks made of fragments from volcanic explosions are known as *pyroclastic,* or "fire-broken," rocks. Those that consist of dense, dark materials are known as *mafic* igneous rocks. On the other hand, those made of lightly colored, less-dense minerals, such as quartz, mica, and feldspar, are called *felsic* igneous rocks. Among the most well known varieties of igneous rock is granite, an intrusive, felsic rock that includes quartz, feldspar, mica, and amphibole in its makeup. Also notable is basalt, which is mafic and extrusive.

Sedimentary Rocks

Earlier, we touched on the subject of consolidation, which can be explained in more depth within the context of sedimentary rock. Consolidation is the compacting of loose materials by any number of processes, including recrystallization and cementation. The first of these processes is the formation of new mineral grains as a result of changes in temperature, pressure, or other factors. In cementation, particles of sediment (material deposited at or near Earth's surface from several sources, most notably preexisting rock) are cemented together, usually with mud.

Compaction, recrystallization, and other processes, such as dehydration (which also may contribute to compaction), are collectively known as diagenesis. The latter term refers to all the changes experienced by a sediment sample under conditions of low temperature and low pressure following deposition. If the temperature and pressure increase, diagenesis may turn into metamorphism, discussed later in the context of metamorphic rock.

Formation of sedimentary rocks. Sedimentary rock is formed by the deposition, compaction, and cementation of rock that has experienced weathering (breakdown of rock due to physical, chemical, or biological processes) or as a result of chemical precipitation. The latter term refers not to "precipitation" in terms of weather but to the formation of a solid from a liquid, by chemical rather than physical means. (The freezing of water, a physical process, is not an example of precipitation.)

Sedimentary rock usually forms at or near the surface of the earth, as the erosive action of wind, water, ice, gravity, or a combination of these forces moves sediment. Yet this formation also may occur when chemicals precipitate from seawater or when organic material, such as plant debris or animal shells, accumulate. Evaporation of saltwater, for instance, produces gypsum, a mineral noted for its lack of thermal conductivity; hence its use in drywall, the material that covers walls in most modern homes. (Ancient peoples made alabaster, a fine-grained ornamental stone, from gypsum.)

Classification and sizes. Sedimentary rock is classified with reference to the size of the particles from which the rock is made as well as the origin of those particles. Clastic rock comes from fragments of preexisting rock (whether igneous, sedimentary, or metamorphic) and organic matter, while nonclastic sedimentary rock is formed either by precipitation or by organic means. Examples include gypsum, salts, and other rocks formed by precipitation of saltwater as well as those created from organic material or organic activity—coal, for example.

Ranging in size from fine clay (less than 0.00015 in., or 0.004 mm) to boulders (defined as any rock larger than 10 in., or 0.254 m), sedimentary rock bears a record of the environment in which the original sediments were deposited. This record lies in the sediment itself. For example, rocks containing conglomerate, material ranging in size from clay to boulders (including the intermediate categories of silt, sand, gravel, pebbles, and cobble), come from sediment that was deposited rapidly as the result of slides or slumps. (Slides and slumps are discussed in Mass Wasting.)



Metamorphic rock is formed by the alteration of preexisting rock. The presence of mica, shown here, is a sign that rock might be metaphorphic. *(© C. D. Winters/Photo Researchers. Reproduced by permission.)*

Sedimentary rocks are of particular interest to paleontologists, stratigraphers, and others working in the field of historical geology, because they are the only kinds of rock in which fossils are preserved. The pressure and temperature levels that produce igneous and metamorphic rock would destroy the organic remnants that produce fossils; on the other hand, sedimentary rock—created by much less destructive processes—permits the formation of fossils. Thus, the study of these formations has contributed greatly to geologists' understanding of the distant past. (See the essays Historical Geology, Stratigraphy, and Paleontology. For more about sedimentary rock, see Sediment and Sedimentation.)

Metamorphic Rocks

Metamorphic rock is formed through the alteration of preexisting rock as a result of changes in temperature, pressure, or the activity of fluids (usually gas or water). These changes in temperature must be extreme (figures are given later), such that the preexisting rock—whether igneous, sedimentary, or metamorphic—is no longer stable.

Often formed in mountain environments, metamorphic rocks include such well-known varieties as marble, slate, and gneiss—metamorphosed forms of limestone, shale, and granite, respectively. Also notable is schist, composed of various minerals, such as talc, mica, and muscovite. There is not always a one-to-one correspondence between precursor rocks and metamorphic ones: increasing temperature and pressure can turn shale progressively into slate, phyllite, schist, and gneiss.

The presence of mica in a rock—or of other minerals, including amphibole, staurolite, and garnet—is a sign that the rock might be metamorphic. These minerals, typical of metamorphic rocks, are known as metamorphic facies. Also indicative of metamorphism are layers in the rock, more or less parallel lines along which minerals are laid as a result of the high pressures applied to the rock in its formation. Metamorphism, the process whereby metamorphic rock is created, also may produce characteristic formations, such as an alignment of elongate crystals or the separation of minerals into layers.

METAMORPHISM. Given the conditions described for metamorphism, one might conclude that in terms of violence, drama, and stress, it is a process somewhere between sedimentation and the formation of igneous rock. That, in fact, is precisely the case: the temperature and pressure conditions necessary for metamorphism lie between those of diagenesis, on the one hand, and the extreme conditions necessary for the production of igneous rock, on the other hand. Specifically, metamorphism occurs at temperatures between 392°F (200°C) and 1,472°F (800°C) and under levels of pressure between 1,000 and 10,000 bars. (A bar is slightly less than the standard atmospheric pressure at sea level. The latter, equal to 14.7 lb. per square inch, or 101,325 Pa, is equal to 1.01325 bars.)

There are several types of metamorphism: regional, contact, dynamic, and hydrothermal. Regional metamorphism results from a major tectonic event or events, producing widespread changes in rocks. Contact or thermal metamorphism results from contact between igneous intrusions and cooler rocks above them, which recrystallize as a result of heating. Dynamic metamorphism takes place in the high-pressure conditions along faults. Finally, hydrothermal metamorphism ensues from contact with fluids

KEY TERMS

ALLOY: A mixture of two or more metals.

CEMENTATION: A process of consolidation whereby particles of sediment are cemented together, usually with mud.

COMPOUND: A substance made up of atoms of more than one element, chemically bonded to one another.

CONGLOMERATE: Unconsolidated rock material containing rocks ranging in size from very small clay (less than 0.00015 in., or 0.004 mm) to boulders (defined as any rock larger than 10 in., or 0.254 m). Sedimentary rock often appears in the form of conglomerate.

CONSOLIDATION: A process whereby materials become compacted, or experience an increase in density. This takes place through several processes, including recrystallization and cementation.

CRYSTALLINE SOLID: A type of solid in which the constituent parts have a simple and definite geometric arrangement that is repeated in all directions.

DEPOSITION: The process whereby sediment is laid down on the Earth's surface.

DIAGENESIS: A term referring to all the changes experienced by a sediment sample under conditions of low temperature and low pressure following deposition. Higher temperature and pressure conditions may lead to metamorphism.

ELEMENT: A substance made up of only one kind of atom. Unlike compounds, elements cannot be broken chemically into other substances.

EROSION: The movement of soil and rock as the result of forces produced by water, wind, glaciers, gravity, and other influences. In most cases, a fluid medium, such as air or water, is involved.

IGNEOUS ROCK: One of the three principal types of rock, along with sedimentary and metamorphic rock. Igneous rock is formed by the crystallization of molten materials, for instance, in a volcano or other setting where plate tectonic processes take place.

LAVA: Molten rock at or near the surface of the earth that becomes igneous rock. Below the surface, lava is known as *magma.*

MAGMA: Molten rock beneath the surface of the earth that becomes igneous rock. Once it is at or near the surface, magma is known as *lava.*

MINERAL: A naturally occurring, typically inorganic substance with a specific chemical composition and a crystalline structure.

MINERALOGY: An area of geology devoted to the study of minerals. Mineralogy includes several subdisciplines, such as crystallography, the study of crystal formations within minerals.

MIXTURE: A substance with a variable composition, meaning that it is composed of molecules or atoms of differing types in varying proportions.

ORE: A rock or mineral possessing economic value.

ORGANIC: At one time, chemists used the term *organic* only in reference to living things. Now the word is applied to most

KEY TERMS CONTINUED

compounds containing carbon and hydrogen, thus excluding carbonates (which are minerals), and oxides such as carbon dioxide.

PETROLOGY: An area of geology devoted to the study of rocks, including their physical properties, distribution, and origins.

PRECIPITATION: In the context of chemistry, precipitation refers to the formation of a solid from a liquid.

RECRYSTALLIZATION: The formation of new mineral grains as a result of changes in temperature, pressure, or other factors.

ROCK: An aggregate of minerals or organic matter, which may be consolidated or unconsolidated.

ROCK CYCLE: The ongoing process whereby rocks continually change from one type to another, typically through melting, metamorphism, uplift, weathering, burial, or other processes.

SAND: A term that can have several meanings. The sand at a beach could be a variety of unconsolidated materials, though most likely it is silica (SiO_2). Sand is also a term used for a size of rock ranging from very fine to very coarse.

SEDIMENT: Material deposited at or near Earth's surface from a number of sources, most notably preexisting rock.

SEDIMENTARY ROCK: One of the three major types of rock, along with igneous and metamorphic rock. Sedimentary rock usually is formed by the deposition, compaction, and cementation of rock that has experienced weathering. It also may be formed as a result of chemical precipitation.

UNCONSOLIDATED ROCK: Rock that appears in the form of loose particles, such as sand.

UPLIFT: A process whereby the surface of Earth rises, owing to either a decrease in downward force or an increase in upward force.

WEATHERING: The breakdown of rocks and minerals at or near the surface of Earth as the result of physical, chemical, or biological processes.

heated by igneous rock. Reacting with minerals in the surrounding rock, the fluids produce different minerals, which, in turn, yield metamorphic rocks.

TYPES OF METAMORPHIC ROCKS. Metamorphic rocks that contain elongate or platy minerals, such as mica and amphibole, are called foliated *rocks.* These rocks have a layered texture, which may manifest as the almost perfect arrangement of materials in slate or as the alternating patterns of light and dark found in some other varieties of rock. Metamorphic rocks without visible layers are referred to as unfoliated rocks. As a foliated metamorphic rock, slate is particularly good for splitting into thin layers—hence one of its most important applications is in making shingles for roofing. By contrast, marble, which is unfoliated, is valued precisely for its lack of tendency to split.

Petrologists attempting to determine exactly which rocks or combinations of rocks metamorphosed to produce a particular sample often face a challenge. Many metamorphic rocks are stubborn about giving up their secrets; on the other hand, it is possible to match up precursor rocks with certain varieties. For example, as noted ear-

lier, marble comes from limestone, while gneiss usually (but not always) comes from granite. Quartzite is metamorphosed sandstone. Nonetheless, it is not as easy to trace the history of a metamorphic rock as it is to say that a raisin was once a grape or that a pickle was once a cucumber.

Where to Find Rocks

In general, one might find igneous rocks such as basalt in any place known for volcanic activity either in the recent or distant past. This would include such well-known areas of volcanism as Hawaii, the Philippines, and Italy, but also places where volcanic activity occurred in the distant past. (See, for instance, the discussion in the essay titled "Paleontology" regarding possible volcanic activity in what is now the continental United States at the conclusion of the Triassic period.)

The best place for metamorphic rock would be in areas of mountain-building and powerful tectonic activity, as for instance in the Himalayas or the Alps of central Europe. Sedimentary rock is basically everywhere, but a good place to find large samples of it would include areas with large oil deposits, which are always found in sedimentary rock.

Closer to home, a wide array of sedimentary rocks can be located in the plains and lowlands of the United States, particularly in the West and Midwest, where large samples are exposed. Igneous and metamorphic rocks can be found, predictably, in regions where mountains provide evidence of past tectonic activity: New England, the Appalachians, and the various mountain ranges of the western United States such as the Rockies, Cascades, and Sierra Nevada.

The Rock Cycle

Given what we have seen about the characteristics of the three rock varieties—igneous, sedimentary, and metamorphic—it should be clear that there is no such thing as a rock that simply is what it is, without any possibility of changing. Rocks, in fact, are constantly changing, as is Earth itself. This process whereby rocks continually change from one type to another—typically through melting, metamorphism, uplift, weathering, burial, or other processes—is known as the rock cycle.

The rock cycle can go something like this: Exposed to surface conditions such as wind and the activity of water, rocks experience weathering. The result is the formation of sediments that are eventually compacted to make sedimentary rocks. As the latter are buried deeper and deeper beneath greater amounts of sediment, the pressure and temperature builds. This process ultimately can result in the creation of metamorphic rock. On the other hand, the rock may undergo such extreme conditions of temperature that it recrystallizes to form igneous rock. Whatever the variety—igneous, sedimentary, or metamorphic—the rock likely will be in a position eventually to experience erosion, in which case the rock cycle begins all over again.

Where to Learn More

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ECONOMIC GEOLOGY

CONCEPT

Economic geology is the study of fuels, metals, and other materials from the earth that are of interest to industry or the economy in general. It is concerned with the distribution of resources, the costs and benefits of their recovery, and the value and availability of existing materials. These materials include ore (rocks or minerals possessing economic value) as well as fossil fuels, which embrace a range of products from petroleum to coal. Rooted in several subdisciplines of the geologic sciences—particularly geophysics, structural geology, and stratigraphy—economic geology affects daily life in myriad ways. Masonry stones and gasoline, gypsum wallboard (sometimes known by the brand name Sheetrock) and jewelry, natural gas, and table salt—these and many more products are the result of efforts in the broad field known as economic geology.

HOW IT WORKS

Background of Economic Geology

Some sources of information in the geologic sciences use a definition of "economic geology" narrower than the one applied here. Rather than including nonmineral resources that develop in and are recovered from a geologic environment—a category that consists primarily of fossil fuels—this more limited definition restricts the scope of economic geology to minerals and ores. Given the obvious economic importance of fossil fuels such as petroleum and its many byproducts as well as coal and peat, however, it seems only appropriate to discuss these valuable organic resources alongside valuable inorganic ones.

The concept of economic geology as such is a relatively new one, even though humans have been extracting metals and minerals of value from the ground since prehistoric times. For all their ability to appreciate the worth of such resources, however, premodern peoples possessed little in the way of scientific theories regarding either their formation or the means of extracting them.

The Greeks, for instance, believed that veins of metallic materials in the earth indicated that those materials were living things putting down roots after the manner of trees. Astrologers of medieval times maintained that each of the "seven planets" (Sun, Moon, and the five planets, besides Earth, known at the time) ruled one of the seven known metals—gold, copper, silver, lead, tin, iron, and mercury—which supposedly had been created under the influence of their respective "planets."

AGRICOLA'S CONTRIBUTION. The first thinker who attempted to go beyond such unscientific (if imaginative) ideas was a German physician writing under the Latinized name Georgius Agricola (1494–1555). As a result of treating miners for various conditions, Agricola, whose real name was Georg Bauer, became fascinated with minerals. The result was a series of written works, culminating with *De re metallica* (On the nature of minerals, 1556, released postthumusly), that collectively initiated the modern subdiscipline of physical geology. (It is worth noting that the first translators of *Metallica* into English were Lou [d. 1944] and Herbert Clark Hoover [1874–1964]. The couple pub-

lished their translation in 1912 in London's *Mining Magazine,* and the husband went on to become the thirty-first president of the United States in 1929.)

Rejecting the works of the ancients and all manner of fanciful explanations for geologic phenomena, Agricola instead favored careful observation, on the basis of which he formed verifiable hypotheses. Regarded as the father of both mineralogy and economic geology, Agricola introduced several ideas that provided a scientific foundation for the study of Earth and its products. In *De ortu et causis subterraneorum* (1546), he critiqued all preceding ideas regarding the formation of ores, including the Greek and astrological notions mentioned earlier as well as the alchemical belief that all metals are composed of mercury and sulfur. Instead, he maintained that subterranean fluids carry dissolved minerals, which, when cooled, leave deposits in the cracks of rocks and thus give rise to mineral veins. Agricola's ideas later helped form the basis for modern theories regarding the formation of ore deposits.

In *De natura fossilium* (On the nature of fossils, 1546), Agricola also introduced a method for the classification of "fossils," as minerals were then known. Agricola's system, which categorizes minerals according to such properties as color, texture, weight, and transparency, is the basis for the system of mineral classification in use today. Of all his works, however, the most important was *De re metallica,* which would remain the leading textbook for miners and mineralogists during the two centuries that followed. In this monumental work, he introduced many new ideas, including the concept that rocks contain ores that are older than the rocks themselves. He also explored in detail the mining practices in use during his time, itself an extraordinary feat in that miners of the sixteenth century tended to guard their trade secrets closely.

Metals, Minerals, and Rocks

Of all known chemical elements, 87, or about 80%, are metals. The latter group is identified as being lustrous or shiny in appearance and malleable or ductile, meaning that they can be molded into different shapes without breaking. Despite their ductility, metals are extremely durable, have high melting and boiling points, and are excellent conductors of heat and electricity. Some, though far from all, register high on the Mohs hardness scale, discussed later in the context of minerals.

The bonds that metals form with each other, or with nonmetals, are known as ionic bonds, the strongest type of chemical bond. Even within a metal, however, there are extremely strong, nondirectional bonds. Therefore, though it is easy to shape metals, it is very difficult to separate metal atoms. Obviously, most metal are solids at room temperature, though this is not true of all: mercury is liquid at ordinary temperatures, and gallium melts at just 85.6°F (29.76°C). Generally, however, metals would be described as crystalline solids, meaning that their constituent parts have a simple and definite geometric arrangement that is repeated in all directions. Crystalline structure is important also within the context of minerals as well as the rocks that contain them.

MINERALS. Whereas there are only 87 varieties of metal, there are some 3,700 types of mineral. There is considerable overlap between metals and minerals, but that overlap is far from complete: many minerals include nonmetallic elements, such as oxygen and silicon. A mineral is a substance that appears in nature and therefore cannot be created artificially, is inorganic in origin, has a definite chemical composition, and possesses a crystalline internal structure.

The term *organic* does not refer simply to substances with a biological origin; rather, it describes any compound that contains carbon, with the exception of carbonates (which are a type of mineral) and oxides, such as carbon dioxide or carbon monoxide. The fact that a mineral must be of nonvarying composition limits minerals almost exclusively to elements and compounds—that is, either to substances that cannot be broken down chemically to yield simpler substances or to substances formed by the chemical bonding of elements. Only in a few highly specific circumstances are naturally occurring alloys, or mixtures of metals, considered minerals.

MINERAL GROUPS. Minerals are classified into eight basic groups:

- Class 1: Native elements
- Class 2: Sulfides
- Class 3: Oxides and hydroxides
- Class 4: Halides

- Class 5: Carbonates, nitrates, borates, iodates
- Class 6: Sulfates, chromates, molybdates, tungstates
- Class 7: Phosphates, arsenates, vanadates
- Class 8: Silicates

The first group, native elements, includes metallic elements that appear in pure form somewhere on Earth; certain metallic alloys, alluded to earlier; as well as native nonmetals, semimetals, and minerals with metallic and nonmetallic elements. The native elements, along with the six classes that follow them in this list, are collectively known as nonsilicates, a term that emphasizes the importance of the eighth group. (For more about the nonsilicates, as well as other subjects covered in the present context, see Minerals.)

The vast majority of minerals, including the most abundant ones, belong to the silicates class, which is built around the element silicon. Just as carbon can form long strings of atoms, particularly in combination with hydrogen (as we discuss in the context of fossil fuels later in this essay), silicon also forms long strings, though its "partner of choice" is typically oxygen rather than hydrogen. Together with oxygen, silicon—known as a metalloid because it exhibits characteristics of both metals and nonmetals—forms the basis for an astonishing array of products, both natural and man-made, which we examine in brief later.

CHARACTERISTICS OF MINERALS. From the list of parameters first developed by Agricola has grown a whole array of characteristics by which minerals are classified. These characteristics also can be used to evaluate an unknown mineral and thus to determine the mineral class within which it fits. One such parameter is the type of crystal of which a mineral is composed. Though there are thousands of minerals, there are just six crystal systems, or basic geometric shapes formed by crystals. Crystallographers, mineralogists concerned with the study of crystal structures, are able to identify the crystal system (the simplest being isometric, or cubic) by studying a good specimen of a mineral and observing the faces of the crystal and the angles at which they meet.

Minerals also can be identified by their hardness, defined as the ability of one mineral to scratch another. Hardness can be measured by the Mohs scale, introduced in 1812 by the German mineralogist Friedrich Mohs (1773–1839), which rates minerals from 1 (talc) to 10 (diamond.) Though it is useful for geologists attempting to identify a mineral in the field, the Mohs scale is not considered helpful for the industrial testing of fine-grained materials, such as steel or ceramics. For such purposes, the Vickers or Knoop scales are applied. These scales (named, respectively, after a British company and an American official) also have an advantage over Mohs in that they offer a precise, proportional scale in which each increase of number indicates the same increase in hardness. By contrast, on the Mohs scale, an increase from 3 to 4 (calcite to fluorite) indicates an additional 25% in hardness, whereas a shift from 9 to 10 (corundum to diamond) marks an increase of 300%.

Other properties significant in identifying minerals are color; streak, or the appearance of the powder produced when one mineral is scratched by a harder one; luster, the appearance of a mineral when light reflects off its surface; cleavage, the planes across which a mineral breaks; fracture, the tendency to break along something other than a flat surface; density, or ratio of mass to volume; and specific gravity, or the ratio between the mineral's density and that of water. Sometimes minerals can be identified in terms of qualities unique to a specific mineral group or groups: magnetism, radioactivity, fluorescence, phosphorescence, and so on. (For more about mineral characteristics, see Minerals.)

ROCKS. A rock is an aggregate of minerals or organic material, which can appear in consolidated or unconsolidated form. Rocks are of three different types: igneous, formed by crystallization of molten minerals, as in a volcano; sedimentary, usually formed by deposition, compaction, or cementation of weathered rock; and metamorphic, formed by alteration of preexisting rock. Rocks made from organic material are typically sedimentary, an example being coal.

Rocks have possessed economic importance from a time long before "economics" as we know it existed—a time when there was nothing to buy and nothing to sell. That time, of course, would be the Stone Age, which dates back practically to the beginnings of the human species and overlapped with the beginnings of civilization some 5,500 years ago. In the hundreds of thousands of years when stone constituted the most advanced

toolmaking material, humans developed an array of stone devices for making fire, sharpening knives, killing animals (and other humans), cutting food or animal skins, and so on.

The Stone Age, both in the popular imagination and (with some qualifications) in actual archaeological fact, was a time when people lived in caves. Since that time, of course, humans have generally departed from the caves, though exceptions exist, as the United States military found in 2001 when attempting to hunt for terrorists in the caves of Afghanistan. In any case, the human attachment to stone dwellings has taken other forms, beginning with the pyramids and continuing through today's masonry homes. Nor is rock simply a structural material for building, as the use of gypsum wallboard, slate countertops, marble finishes, and graveled walkways attests. And, of course, construction is only one of many applications to which rocks and minerals are directed, as we shall see.

Hydrocarbons

As noted earlier, the focus of economic geology is on both rocks and minerals, on the one hand, and fossil fuels, on the other. The latter may be defined as fuel (specifically, coal, oil, and gas) derived from deposits of organic material that have experienced decomposition and chemical alteration under conditions of high pressure. Given this derivation from organic material, by definition all fossil fuels are carbon-based, and, specifically, they are built around hydrocarbons—chemical compounds whose molecules are made up of nothing but carbon and hydrogen atoms.

Theoretically, there is no limit to the number of possible hydrocarbons. Carbon forms itself into apparently limitless molecular shapes, and hydrogen is a particularly versatile chemical partner. Hydrocarbons may form straight chains, branched chains, or rings, and the result is a variety of compounds distinguished not by the elements in their makeup or even (in some cases) by the numbers of different atoms in each molecule, but rather by the structure of a given molecule.

VARIETIES OF HYDROCARBON. Among the various groups of hydrocarbons are alkanes or saturated hydrocarbons, so designated because all the chemical bonds are filled to their capacity (that is, "saturated") with hydrogen atoms. Included among them are such familiar names as methane (CH_4), ethane (C_2H_6), propane (C_3H_8), and butane (C_4H_{10}). The first four, being the lowest in molecular mass, are gases at room temperature, while the heavier ones—including octane (C_8H_{18})—are oily liquids. Alkanes even heavier than octane tend to be waxy solids, an example being paraffin wax, for making candles.

With regard to octane, incidentally, there is a reason why its name is so familiar, while that of heptane (C_7H_{16}) is not. Heptane does not fire smoothly in an internal-combustion engine and therefore disrupts the engine's rhythm. For this reason, it has a rating of zero on a scale of desirability, while octane has a rating of 100. This is why gas stations list octane ratings at the pump: the higher the content of octane, the better the gas is for one's automobile.

In a hydrocarbon chain, if one or more hydrogen atoms is removed, a new bond may be formed. The hydrocarbon chain is then named by adding the suffix *yl*—hence such names as methyl, ethyl, and so on. This indicates that the substance is an alkane, and that something other than hydrogen can be attached to the chain; for example, the attachment of a chlorine atom could yield methyl chloride. Two other large structural groups of hydrocarbons are alkenes and alkynes, which contain double or triple bonds between carbon atoms. Such hydrocarbons are unsaturated—in other words, if the double or triple bond is broken, some of the carbon atoms are then free to form other bonds. Among the products of these groups is the alkene known as acetylene, or C_2H_2, used for welding steel. In addition to alkanes, alkenes, and alkynes, all of which tend to form carbon chains, there are the aromatic hydrocarbons, a traditional name that actually has nothing to do with smell.

All aromatic hydrocarbons contain what is known as a benzene ring, which has the chemical formula C_6H_6 and appears in characteristic ring shapes. In this group are such products as naphthalene, toluene, and dimethyl benzene. These last two are used as solvents as well as in the synthesis of drugs, dyes, and plastics. One of the more famous (or infamous) products in this part of the vast hydrocarbon network is trinitrotoluene, or TNT. Naphthalene is derived from coal tar and used in the synthesis of other compounds. A crystalline solid with a powerful odor,

it is found in mothballs and various deodorant disinfectants.

REAL-LIFE APPLICATIONS

Fossil Fuels

The organic material that has decomposed to create the hydrocarbons in fossil fuels comes primarily from dinosaurs and prehistoric plants, though it just as easily could have come from any other organisms that died in large numbers a long, long time ago. To form petroleum, there must be very large quantities of organic material deposited along with sediments and buried under more sediment. The accumulated sediments and organic material are called *source rock*.

What happens after accumulation of this material is critical and depends a great deal on the nature of the source rock. It is important that the organic material—for example, the vast numbers of dinosaurs that died in a mass extinction about 65 million years ago (see Paleontology)—not be allowed simply to rot, as would happen in an aerobic, or oxygen-containing, environment. Instead, the organic material undergoes transformation into hydrocarbons as a result of anaerobic chemical activity, or activity that takes place in the absence of oxygen.

Good source rocks for this transformation are shale or limestone, provided the particular rocks are composed of between 1% and 5% organic carbon. The source rocks should be deep enough that the pressure heats the organic material, yet not so deep that the pressure and temperature cause the rocks to undergo metamorphism or transform them into graphite or other non-hydrocarbon versions of carbon. Temperatures of up to 302°F (150°C) are considered optimal for petroleum generation.

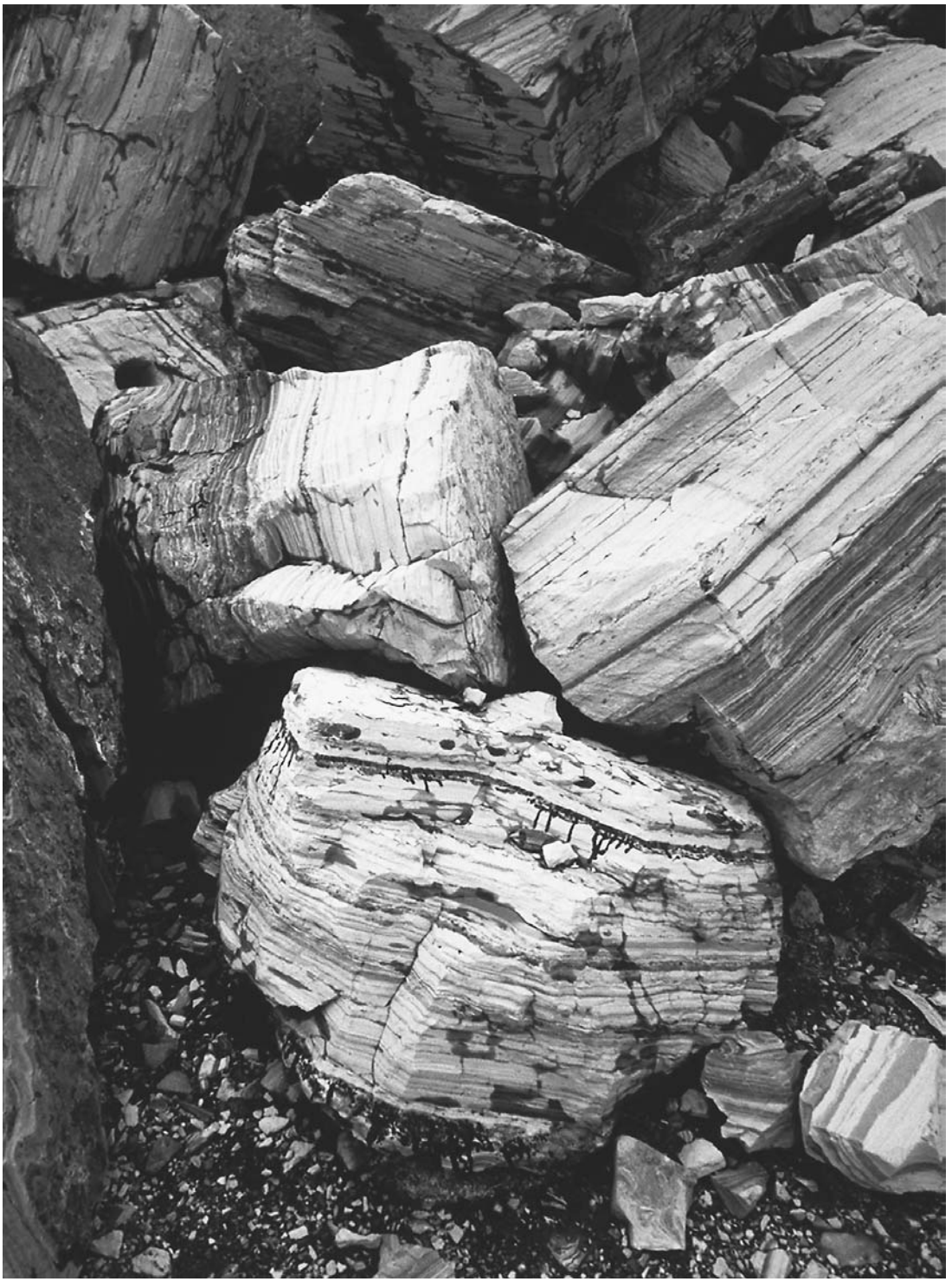
Once generated, petroleum gradually moves from the source rock to a reservoir rock, or a rock that stores petroleum in its pores. A good reservoir rock is one in which the pore space constitutes more than 30% of the rock volume. Yet the rock must be sealed by another rock that is much less porous; indeed, for a seal or cap rock, as it is called, a virtually impermeable rock is preferred. Thus, the best kind of seal-forming rock is one made of very small, closely fitting pieces of sediment, for instance, shale. Such a rock is capable of holding petroleum in place for millions of years until it is ready to be discovered and used.

HUMANS AND PETROLEUM. People have known about petroleum from prehistory, simply because there were places on Earth where it literally seeped from the ground. The modern era of petroleum drilling, however, began in 1853, when an American lawyer named George Bissell (1821–1884) recognized its potential for use as a lamp fuel. He hired "Colonel" Edwin Drake (1819–1880) to oversee the drilling of an oil well at Titusville, Pennsylvania, and in 1859 Drake struck oil. The legend of "black gold," of fortunes to be made by drilling holes in the ground, was born.

In the wake of the development and widespread application of the internal-combustion engine during the latter part of the nineteenth and the early part of the twentieth centuries, interest in oil became much more intense, and wells sprouted up around the world. Sumatra, Indonesia, yielded oil from its first wells in 1885, and in 1901, successful drilling began in Texas—the source of many a Texas-sized fortune. An early form of the company known today as British Petroleum (BP) discovered the first Middle Eastern oil in Persia (now Iran) in 1908. Over the next 50 years, the economic importance and prospects of that region changed considerably.

With the vast expansion in automobile ownership that began following World War I (1914–1918) and reached even greater heights after World War II (1939–1945), the value and importance of petroleum soared. The oil industry boomed, and, as a result, many geologists found employment in a sector that offered far more in the way of financial benefits than university or government positions ever could. Today geologists assist their employers in locating oil reserves, not an easy task because so many variables must line up to produce a viable oil source. Given the cost of drilling a new oil well, which may run to $30 million or more, it is clearly important to exercise good judgment in assessing the possibilities of finding oil.

The oil industry has been fraught with environmental concerns over the impact of drilling (much of which takes place offshore, on rigs placed in the ocean); possible biohazards associated with spills, such as the one involving the Exxon *Valdez* in 1989; and the effect on the



Blocks of shale at the Paraho Oil Shale Facility in Colorado. Shale is known as a seal or cap rock, a virtually impermeable rock made of small, closely fitting pieces of sediment that covers a more porous rock holding petroleum. *(© U.S. Department of Energy/Photo Researchers. Reproduced by permission.)*

atmosphere of carbon monoxide and other greenhouse gases produced by petroleum-burning internal-combustion engines. There is even more wide-ranging concern over United States dependence on oil sources in foreign countries (some of which are openly hostile to the United States) as well as the possible dwindling of resources.



Offshore oil rig at Sabine Pass, Texas. *(© Garry D. McMichael/Photo Researchers. Reproduced by permission.)*

At the present rate of consumption, oil reserves will be exhausted by about the year 2040, but this takes into account only reserves that are considered viable today. As exploration continues, the tapping of United States reserves, such as those in Alaska, will become more and more profitable, leading to increased exploitation of U.S. resources and decreased dependence on oil produced by Middle Eastern states, many of which openly or covertly support terrorist attacks against the United States. In the long run, however, it will be necessary to develop new means of fueling the industrialized world, because petroleum is a nonrenewable resource: there is only so much of it underground, and when it is gone, it will not be replaced for millions of years (if at all).

PETROCHEMICALS. In the meantime, however, petroleum—a mixture of alkanes, alkenes, and aromatic hydrocarbons—makes the world (or at least the industrialized world) go 'round. Petroleum itself is a raw material from which numerous products, collectively known as petrochemicals or petroleum derivatives, are obtained. Through a process termed fractional distillation, the petrochemicals of the lowest molecular mass boil off first, and those having higher mass separate at higher temperatures.

Natural gas separates from petroleum at temperatures below 96.8°F (36°C)—far lower than the boiling point of water. At somewhat higher temperatures, petroleum ether and naphtha, both solvents (naphtha is used in paint thinner), separate; then, in the region between 156.2°F and 165.2°F (69–74°C), gasoline separates. Still higher temperatures yield other substances, each thicker than the one before it: kerosene; fuel for heating and the operation of diesel engines; lubricating oils; petroleum jelly; paraffin wax; and pitch, or tar. A host of other organic chemicals, including various drugs, plastics, paints, adhesives, fibers, detergents, synthetic rubber, and agricultural chemicals, owe their existence to petrochemicals.

Silicon, Silicates, and Other Compounds

It was stated earlier that both carbon and silicon have the tendency to produce long strings of atoms, usually in combination with hydrogen in the first case and oxygen in the second. This is no accident, since silicon lies just below carbon on the periodic table of elements and they share certain chemical features (see Minerals). Just as carbon is at the center of a vast world of hydrocarbons, so silicon is equally important to inorganic

substances ranging from sand or silica (SiO_2) to silicone (a highly versatile set of silicon-based products), to the rocks known as silicates.

Silicates are the basis for several well-known mineral types, including garnet, topaz, zircon, kaolinite, talc, mica, and the two most abundant minerals on Earth, feldspar and quartz. (Note that most of the terms used here refer to a group of minerals, not to a single mineral.) Made of compounds formed around silicon and oxygen and comprising various metals, such as aluminum, iron, sodium, and potassium, the silicates account for 30% of all minerals. As such, they appear in everything from gemstones to building materials; yet they are far from the only notable products centered around silicon.

Silicone and other compounds. Silicone is not a mineral; rather, it is a synthetic product often used as a substitute for organic oils, greases, and rubber. Instead of attaching to oxygen atoms, as in a silicate, silicon atoms in silicone attach to organic groups, that is, molecules containing carbon. Silicone oils frequently are used in place of organic petroleum as a lubricant because they can withstand greater variations in temperature. And because the body tolerates the introduction of silicone implants better than it does organic ones, silicones are used in surgical implants as well. Silicone rubbers appear in everything from bouncing balls to space vehicles, and silicones are also present in electrical insulators, rust preventives, fabric softeners, hair sprays, hand creams, furniture and automobile polishes, paints, adhesives, and even chewing gum.

Even this list does not exhaust the many applications of silicon, which (together with oxygen) accounts for the vast majority of the mass in Earth's crust. Owing to its semimetallic qualities, silicon is used as a semiconductor of electricity. Computer chips are tiny slices of ultrapure silicon, etched with as many as half a million microscopic and intricately connected electronic circuits. These chips manipulate voltages using binary codes, for which 1 means "voltage on" and 0 means "voltage off." By means of these pulses, silicon chips perform multitudes of calculations in seconds—calculations that would take humans hours or months or even years.

A porous form of silica known as silica gel absorbs water vapor from the air and is often packed alongside moisture-sensitive products, such as electronics components, to keep them dry. Silicon carbine, an extremely hard crystalline material manufactured by fusing sand with coke (almost pure carbon) at high temperatures, has applications as an abrasive.



Silicone, a synthetic product, has a variety of uses, from electrical insulators to fabric softeners to paints and adhesives. It is tolerated better by the human body than organic compounds and often is used for surgical implants. *(© Michelle Del Guercio/Photo Researchers. Reproduced by permission.)*

Ores

Earlier, it was stated that an ore is a rock or mineral that possesses economic value. This is true, but a more targeted definition would include the adjective metalliferous, since economically valuable minerals that contain no metals usually are treated as a separate category, industrial minerals. Indeed, it can be said that the interests of economic geology are divided into three areas: ores, industrial minerals, and fuels, which we have discussed already.

The very word ore seems to call to mind one of the oldest-known metals in the world and probably the first material worked by prehistoric metallurgists: gold. Even the Spanish word for gold, *oro,* suggests a connection. When conquistadors from Spain arrived in the New World after about 1500, *oro* was their obsession, and it was

said that the Spanish invaders of Mexico found every bit of gold or silver ore located at the surface of the earth. However, miners of the sixteenth century lacked much of the knowledge that helps geologists today find ore deposits that are *not* at the surface.

LOCATING AND EXTRACTING ORES. The modern approach uses knowledge gained from experience. As in Agricola's day, much of the wealth possessed by a mining company is in the form of information regarding the means of best seeking out and retrieving materials from the solid earth. Certain surface geochemical and geophysical indicators help direct the steps of geologists and miners searching for ore. Thus, by the time a company in search of ore begins drilling, a great deal of exploratory work has been done. Only at that point is it possible to determine the value of the deposits, which may simply be minerals of little economic interest.

It is estimated that a cubic mile (1.6 km^3) of average rock contains about $1 trillion worth of metals, which at first sounds promising—until one does the math. A trillion dollars is a lot of money, but 1 cu. mi. (equal to 5,280 × 5,280 × 5,280 ft., or 1,609 km^3) is a lot of space too. The result is that 1 cu. ft. (0.028 m^3) is worth only about $6.79. But that is an average cubic foot in an average cubic mile of rock, and no mining company would even consider attempting to extract metals from an average piece of ground. Rather, viable ore appears only in regions that have been subjected to geologic processes that concentrate metals in such a way that their abundance is usually many hundreds of times greater than it would be on Earth as a whole.

Ore contains other minerals, known as *gangue,* which are of no economic value but which serve as a telltale sign that ore is to be found in that region. The presence of quartz, for example, may suggest deposits of gold. Ore may appear in igneous, metamorphic, or sedimentary deposits as well as in hydrothermal fluids. The latter are emanations from igneous rock, in the form of gas or water, that dissolve metals from rocks through which they pass and later deposit the ore in other locations.

CONFRONTING THE HAZARDS OF MINING. Mining, a means of extracting not only ores but many industrial minerals and fuels, such as coal, is difficult work fraught with numerous hazards. There are short-term dangers to the miners, such as cave-ins, flooding, or the release of gases in the mines, as well as long-term dangers that include such mining-related diseases as black lung (typically a hazard of coal miners). Then there is the sheer mental and emotional stress that comes from spending eight or more hours a day away from the sunlight, in claustrophobic surroundings.

And, of course, there is the environmental stress created by mining—not just by the immediate impact of cutting a gash in Earth's surface, which may disrupt ecosystems on the surface, but myriad additional problems, such as the seepage of pollutants into the water table. Abandoned mines present further dangers, including the threat of subsidence, which make these locations unsafe for the long term.

Higher environmental and occupational safety standards, established in the United States during the last third of the twentieth century, have led to changes in the way mining is performed as well as in the way mines are left when the work is completed. For example, mining companies have experimented with the use of chemicals or even bacteria, which can dissolve a metal underground and allow it to be pumped to the surface without the need to create actual underground shafts and tunnels or to send human miners to work them.

Industrial Minerals and Other Products

Industrial minerals, as noted earlier, are nonmetal-containing mineral resources of interest to economic geology. Examples include asbestos, a generic term for a large group of minerals that are highly resistant to heat and flame; boron compounds, which are used for making heat-resistant glass, enamels, and ceramics; phosphates and potassium salts, used in making fertilizers; and sulfur, applied in a range of products, from refrigerants to explosives to purifiers used in the production of sugar.

Just one industrial mineral, corundum (from the oxides class of mineral), can have numerous uses. Extremely hard, corundum in the form of an unconsolidated rock commonly called emery has been used as an abrasive since ancient times. Owing to its very high melting point—even higher than that of iron—corundum also is employed in making alumina, a fire-

KEY TERMS

ALLOY: A mixture of two or more metals.

ATOM: The smallest particle of an element, consisting of protons, neutrons, and electrons. An atom can exist either alone or in combination with other atoms in a molecule.

CHEMICAL BONDING: The joining through electromagnetic force of atoms that sometimes, but not always, represent more than one chemical element.

COMPOUND: A substance made up of atoms of more than one element, chemically bonded to one another.

CONSOLIDATION: A process whereby materials become compacted, or experience an increase in density.

CRYSTALLINE SOLID: A type of solid in which the constituent parts have a simple and definite geometric arrangement that is repeated in all directions.

DEPOSITION: The process whereby sediment is laid down on the Earth's surface.

DUCTILE: Capable of being bent or molded into various shapes without breaking.

ECONOMIC GEOLOGY: The study of fuels, metals, and other materials from the Earth that are of interest to industry or the economy in general.

ELECTRON: A negatively charged particle in an atom, which spins around the nucleus.

FOSSIL FUELS: Fuel derived from deposits of organic material that have experienced decomposition and chemical alteration under conditions of high pressure. These nonrenewable forms of bioenergy include petroleum, coal, peat, natural gas, and their derivatives.

GANGUE: Minerals of no economic value, which appear in nature with ore. Recognition of certain characteristic combinations can help geologists find ore on the basis of its attendant gangue. (The *ue* is silent, as in *tongue.*)

HARDNESS: In mineralogy, the ability of one mineral to scratch another. This can be measured by the Mohs scale.

HYDROCARBON: Any organic chemical compound whose molecules are made up of nothing but carbon and hydrogen atoms.

IGNEOUS ROCK: One of the three principal types of rock, along with sedimentary and metamorphic rock. Igneous rock is formed by the crystallization of molten materials, for instance, in a volcano or other setting where plate tectonic processes take place.

INDUSTRIAL MINERALS: Nonmetallic minerals with uses for industry.

LUSTER: The appearance of a mineral when light reflects off its surface. Among the terms used in identifying luster are metallic, vitreous (glassy), and dull.

METALS: Substances that are ductile, lustrous or shiny in appearance, extremely durable, and excellent conductors of heat and electricity. Metals have very high melting and boiling points, and some (though far from all) have a high degree of hardness.

KEY TERMS CONTINUED

METAMORPHIC ROCK: One of the three principal varieties of rock, along with sedimentary and igneous rock. Metamorphic rock is formed through the alteration of preexisting rock as a result of changes in temperature, pressure, or the activity of fluids. These changes are known as metamorphism.

MINERAL: A naturally occurring, typically inorganic substance with a specific chemical composition and a crystalline structure. Unknown minerals usually can be identified in terms of specific parameters, such as hardness or luster.

MINERALOGY: An area of geology devoted to the study of minerals. Mineralogy includes a number of subdisciplines, such as crystallography, or the study of crystal formations within minerals.

MOHS SCALE: A scale introduced in 1812 by the German mineralogist Friedrich Mohs (1773–1839) that rates the hardness of minerals from 1 to 10. Ten is equivalent to the hardness of a diamond and 1 that of talc, an extremely soft mineral.

MOLECULE: A group of atoms, usually but not always representing more than one element, joined in a structure. Compounds are typically made up of molecules.

NUCLEUS: The center of an atom, a region where protons and neutrons are located and around which electrons spin.

ORE: A metalliferous rock or mineral possessing economic value.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon and hydrogen, thus excluding carbonates (which are minerals), and oxides such as carbon dioxide.

PHYSICAL GEOLOGY: The study of the material components of Earth and of the forces that have shaped the planet. Physical geology is one of two principal branches of geology, the other being historical geology.

PROTON: A positively charged particle in an atom.

ROCK: An aggregate of minerals or organic matter, which may be consolidated or unconsolidated.

SEDIMENT: Material deposited at or near Earth's surface from a number of sources, most notably preexisting rock.

SEDIMENTARY ROCK: One of the three major types of rock, along with igneous and metamorphic rock. Sedimentary rock usually is formed by the deposition, compaction, and cementation of rock that has experienced weathering. It also may be formed as a result of chemical precipitation.

STREAK: The color of the powder produced when one mineral is scratched by another, harder one.

UNCONSOLIDATED ROCK: Rock that appears in the form of loose particles, such as sand.

proof product used in furnaces and fireplaces. Though pure corundum is colorless, trace amounts of certain elements can yield brilliant colors: hence, corundum with traces of chromium becomes a red ruby, while traces of iron, titanium, and other elements yield varieties of sap-

phire in yellow, green, and violet as well as the familiar blue.

AN ARRAY OF APPLICATIONS. We have only begun to scratch the surface, as it were, of the uses to which minerals can be put: after all, everything—literally, every solid object—that people use is either organic in origin or a mineral. The wide array of applications of minerals is clear from the following list of mineral categories, classified by application: abrasives (corundum, diamond), ceramics (feldspar, quartz), chemical minerals (halite, sulfur, borax), and natural pigments (hematite, limonite).

Lime, cement, and plaster comes from calcite and gypsum, while building materials—both structural and ornamental—are products of agate, as well as the two aforementioned minerals. Table salt is a mineral, and so is chalk, as are countless other products. There are rocks, such as granite and marble, used in building, decoration, or artwork, and then there are "rocks"—to use a word that is at once a geologic term and a slang expression—that appear in the form of jewelry.

JEWELRY. Out of all minerals, 16 are important for their use as gems: beryl, chrysoberyl, corundum, diamond, feldspar, garnet, jade, lazurite, olivine, opal, quartz, spinel, topaz, tourmaline, turquoise, and zircon. Not all forms of these minerals, of course, are precious. Furthermore, some minerals provide more than one type of gem: corundum, as we have noted, is a source of rubies and sapphires, while beryl produces both emeralds and aquamarines.

Note that many of the precious gems familiar to most of us are not minerals in their own right but versions of minerals. At least one, the pearl, is not on this list because, with its organic origin, it is not a mineral. Certainly not all minerals are created equal: even in the list of 16 just provided, the name *diamond* stands out, representing a worldwide standard of value. Yet a diamond is nothing but pure carbon, which also appears in the form of graphite and (with a very few impurities) as coke for burning.

A diamond is unusual, however, in many respects, including the fact that it is basically a huge "molecule" composed of carbon atoms strung together by chemical bonds. The size of this formation corresponds to the size of the diamond, such that a diamond of 1 carat is simply a gargantuan "molecule" containing about 10^{22} (10,000,000,000,000,000,000,000, or 10 billion trillion) carbon atoms. Not only is a diamond rare and (when properly selected, cut, and polished) extremely beautiful, it is also extraordinarily hard. At the top of the Mohs scale, it can cut any other substance, but nothing can cut a diamond except another diamond.

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GEOPHYSICS

GRAVITY AND GEODESY

GEOMAGNETISM

CONVECTION

ENERGY AND EARTH

GRAVITY AND GEODESY

CONCEPT

Thanks to the force known as gravity, Earth maintains its position in orbit around the Sun, and the Moon in orbit around Earth. Likewise, everything on and around Earth holds its place—the waters of the ocean, the gases of the atmosphere, and so on—owing to gravity, which is also the force that imparts to Earth its nearly spherical shape. Though no one can really say what gravity *is,* it can be quantified in terms of mass and the inverse of the distance between objects. Earth scientists working in the realm of geophysics known as geodesy measure gravitational fields, as well as anomalies within them, for a number of purposes, ranging from the prediction of tectonic processes to the location of oil reserves.

HOW IT WORKS

Gravitation

Not only does gravity keep Earth and all other planets in orbit around the Sun, it also makes it possible for our solar system to maintain its position in the Milky Way, rather than floating off through space. Likewise, the position of our galaxy within the larger universe is maintained because of gravity. As for the universe itself, though many questions remain about its size, mass, and boundaries, it seems clear that the cosmos is held together by gravity.

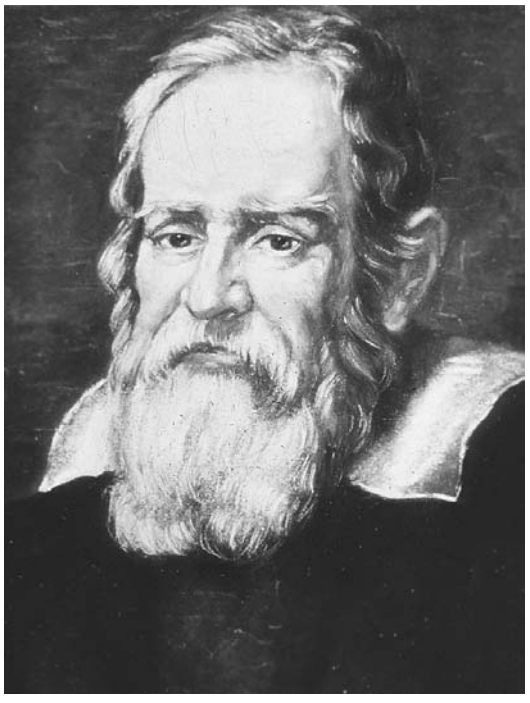
Thanks to gravity, all objects on Earth as well as those within its gravitational field remain fixed in place. These objects include man-made satellites, which have grown to number in the thousands since the first was launched in 1957, as well as the greatest satellite of them all: the Moon. Even though people are accustomed to thinking of gravity in these large terms, with regard to vast bodies such as Earth or the Moon, every object in the universe, in fact, exerts some gravitational pull on another.

This attraction is proportional to the product of the mass of the two bodies, and inversely related to the distance between them. Bodies have to be fairly large (i.e., larger than an asteroid) for this attraction to be appreciable, but it is there, and thus gravity acts as a sort of "glue" holding together the universe. As to what gravity really is or exactly why it works, both of which are legitimate questions, the answers have so far largely eluded scientists.

Present-day scientists are able to understand how gravity works, however, inasmuch as it can be described as a function of mass and the gravitational constant (discussed later) and an inverse function of distance. They also are able to measure gravitational fields and anomalies within them. That, in fact, is the focus of geodesy, an area of geophysics devoted to the measurement of Earth's shape and gravitational field.

Discovering Gravity

As discussed in several places within this book (see the entries Earth, Science, and Nonscience and Studying Earth), the physical sciences made little progress until the early sixteenth century. For centuries, the writings of the Greek philosopher Aristotle (384–322 B.C.) and the Alexandrian astronomer Ptolemy (*ca.* A.D. 100–170) had remained dominant, reinforcing an almost entirely erroneous view of the universe. This Aristotelian/Ptolemaic universe had Earth at its



Galileo Galilei *(Corbis-Bettmann. Reproduced by permission.)*

center, with the Sun, Moon, and other planets orbiting it in perfect circles.

The discovery by the Polish astronomer Nicolaus Copernicus (1473–1543) that Earth rotates on its axis and revolves around the Sun ultimately led to the overturning of the Ptolemaic model. This breakthrough, which inaugurated the Scientific Revolution (*ca.* 1550–1700), opened the way for the birth of physics, chemistry, and geology as genuine sciences. Copernicus himself was a precursor to this revolution rather than its leader; by contrast, the Italian astronomer Galileo Galilei (1564–1642) introduced the principles of study, known as the scientific method, that govern the work of scientists to this day.

Galileo and gravitational acceleration. Galileo applied his scientific method in his studies of falling objects and was able to show that objects fall as they do, not because of their weight (as Aristotle had claimed) but as a consequence of gravitational force. This meant that the acceleration of all falling bodies would have to be the same, regardless of weight.

Of course, everyone knows that a stone falls faster than a feather, but Galileo reasoned that this was a result of factors other than weight, and later investigations confirmed that air resistance, rather than weight, is responsible for this difference. In other words, a stone falls faster than a feather not because it is heavier but because the feather encounters greater air resistance. In a vacuum, or an area devoid of all matter, including air, they would fall at the same rate.

On the other hand, if one drops two objects that meet similar air resistance but differ in weight—say, a large stone and a smaller one—they fall at almost exactly the same rate. To test this hypothesis directly, however, would have been difficult for Galileo: stones fall so fast that even if dropped from a great height, they would hit the ground too soon for their rate of fall to be tested with the instruments then available.

Instead, Galileo used the motion of a pendulum and the behavior of objects rolling or sliding down inclined planes as his models. On the basis of his observations, he concluded that all bodies are subject to a uniform rate of gravitational acceleration, later calibrated at 32 ft. (9.8 m) per second per second. What this means is that for every 32 ft. an object falls, it is accelerating at a rate of 32 ft. per second as well; hence, after two seconds it falls at the rate of 64 ft. per second, after three seconds it falls at 96 ft. per second, and so on.

Newton's breakthrough. Building on the work of his distinguished forebear, Sir Isaac Newton (1642–1727), who was born the same year Galileo died, developed a paradigm for gravitation that even today explains the behavior of objects in virtually all situations throughout the universe. Indeed, the Newtonian model reigned supreme until the early twentieth century, when Albert Einstein (1879–1955) challenged it on certain specifics.

Even so, Einstein's relativity did not *disprove* the Newtonian system as Copernicus and Galileo had disproved Aristotle's and Ptolemy's theories; rather, it showed the limitations of Newtonian mechanics for describing the behavior of certain objects and phenomena. In the ordinary world of day-to-day experience, however, the Newtonian system still offers the key to how and why things work as they do. This is particularly the case with regard to gravity.

Understanding the Law of Universal Gravitation

Like Galileo, Newton began in part with the aim of testing hypotheses put forward by an

astronomer—in this case, Johannes Kepler (1571–1630). In the early years of the seventeenth century, Kepler published his three laws of planetary motion, which together identified the elliptical (oval-shaped) path of the planets around the Sun. Kepler had discovered a mathematical relationship that connected the distances of the planets from the Sun to the period of their revolution around it. Like Galileo with Copernicus, Newton sought to generalize these principles to explain not only *how* the planets moved but also *why* they did so.

The result was Newton's *Philosophiae naturalis principia mathematica* (Mathematical principles of natural philosophy, 1687). Usually referred to simply as the *Principia,* the book proved to be one of the most influential works ever written. In it, Newton presented his law of universal gravitation, along with his three laws of motion. These principles offered a new model for understanding the mechanics of the universe.

The Three Laws of Motion

Newton's three laws of motion may be summarized in this way:

- An object at rest will remain at rest, and an object in motion will remain in motion at a constant velocity unless and until outside forces act upon it.
- The net force acting upon an object is a product of its mass multiplied by its acceleration.
- When one object exerts a force on another, the second object exerts on the first a force equal in magnitude but opposite in direction.

The first law of motion identifies inertia, a concept introduced by Galileo to explain what kept the planets moving around the Sun. Inertia is the tendency of an object either to keep moving or to keep standing still, depending on what it is already doing. Note that the first law refers to an object moving at a constant velocity: velocity is speed in a certain direction, so a constant velocity would be the same speed in the same direction.

Inertia is measured by mass, which—as the second law states—is a component of force and is inversely related to acceleration. The latter, as defined by physics, has a much broader meaning than it usually is given in ordinary life. Acceleration does not mean simply an increase of speed for an object moving in a straight line; rather, it is a change in velocity—that is, a change of speed or direction or both.

By definition, then, rotational motion (such as that of Earth around the Sun) involves acceleration, because any movement other than motion in a straight line at a constant speed requires a change in velocity. This further means that an object experiencing rotational motion *must* be under the influence of some force. That force is gravity, and as the third law shows, every force exerted in one direction is matched by an equal force in the opposing direction. (This law is sometimes rendered "For every action there is an equal and opposite reaction.")

Newton's gravitational formula. The law of universal gravitation can be stated as a formula for calculating the gravitational attraction between two objects of a certain mass, m_1 and m_2: $F_{grav} = G \times (m_1 m_2)/r^2$. In this equation, F_{grav} is gravitational force, and r^2 is the square of the distance between the two objects.

As for *G,* in Newton's time the value of this number was unknown. Newton was aware simply that it represented a very small quantity: without it, $(m_1 m_2)/r^2$ could be quite sizable for objects of relatively great mass separated by a relatively small distance. When multiplied by this very small number, however, the gravitational attraction would be revealed to be very small as well. Only in 1798, more than a century after Newton's writing, did the English physicist Henry Cavendish (1731–1810) calculate the value of *G* using a precision instrument called a torsion balance.

The value of *G* is expressed in units of force multiplied by distance squared, and then divided by,mass squared; in other words, *G* is a certain value of $(N \times m^2)/kg^2$, where *N* stands for newtons, *m* for meters, and *kg* for kilograms. Nor is the numerical value of *G* a whole number such as 1. A figure as large as 1, in fact, is astronomically huge compared with *G,* whose value is 6.67×10^{-11}—in other words, 0.0000000000667.

Physical Geodesy

Within the realm of geodesy is that of physical geodesy, which is concerned specifically with the measurement of Earth's gravitational field as well as the geoid. The latter may be defined as a surface of uniform gravitational potential covering the

entire Earth at a height equal to sea level. ("Potential" here is analogous to height or, more specifically, position in a field. For a discussion of potential in a gravitational field, see Energy and Earth.)

Thus, in areas that are above sea level, the geoid would be below ground—indeed, *far* below it in mountainous regions. Yet in some places (most notably the Dead Sea and its shores, the lowest point on Earth), it would be above the solid earth and waters. The geoid is also subject to deviations or anomalies, owing to the fact that the planet's mass is not distributed uniformly; in addition, small temporary disturbances in the geoid may occur on the seas as a result of wind, tides, and currents.

Generally speaking, however, the geoid is a stable reference platform from which to measure gravitational anomalies. It is a sort of imaginary gravitational "skin" covering the planet, and in the past, countries conducting geodetic surveys tended to choose a spot within their boundaries as the reference point for all measurements. With the development of satellites and their use for geodetic research, however, it has become more common for national geodetic societies to use global points of reference such as the planet's center of mass.

MEASUREMENTS FROM SPACE, LAND, AND SEA. The geoid can be determined by using such a satellite, equipped with a radar altimeter, but there is also the much older technique of terrestrial gravity measurement. The terrestrial method is much more difficult and prone to error, however, and calculations require detailed checking and correction to remove potential anomalies due to the presence of matter in areas above the points at which gravitational measurements were obtained.

Also highly subject to error are measurements made from a vessel at sea. This has to do not only with the effect of the ship's pitch and roll but also with something called the Eötvös effect. Named for the Hungarian physicist Baron Roland Eötvös (1848–1919), who conducted extensive studies on gravity, the effect is related to the Coriolis force, which causes the deflection of atmospheric and oceanic currents in response to Earth's rotation. Measurements of gravity from the air are also subject to the Eötvös effect, though the use of GPS (global positioning system) information, obtained from satellites, can improve greatly the accuracy of seaborne measurements.

HOW GRAVITY IS MEASURED. Scientists can obtain absolute terrestrial gravity measurements by measuring the amount of time it takes for a pellet to fall a certain distance within a vacuum—that is, a chamber from which all matter, including air, has been removed. This, of course, is the same technology Galileo used in making his observations more than 400 years ago. It is also possible to obtain relative gravity measurements with the use of mechanical balance instruments.

As noted earlier, the acceleration due to gravity is 9.8 m/s^2, or 9.8 $m\ s^{-2}$. (Scientists sometimes use the latter notation, in which the minus sign is not meant to indicate a negative but rather is used in place of "per".) This number is the measure of Earth's gravitational field. In measuring gravitational anomalies, scientists may use the Gal, named after Galileo, which is equal to 0.01 m/s^2. Typically, however, the milligal, equal to one-thousandth of a Gal, is used. Note that "Gal" sometimes is rendered in lowercase, but this can be confusing, because it looks like the abbreviation for "gallon.")

WHY MEASURE GRAVITY? Why is it important to measure gravity and gravitational anomalies? One answer is that weight values can vary considerably, depending on one's position relative to Earth's gravitational field. A fairly heavy person might weigh as much as a pound less at the equator than at the poles and less still at the top of a high mountain. The value of the gravity field at sea level has a range from 9.78 to 9.83 m/s^2, a difference of about 50,000 g.u., and it is likely to be much lower than 9.78 m/s^2 at higher altitudes.

Indeed, the higher one goes, the weaker Earth's gravitational field becomes. At the same time, the gases of the atmosphere dissipate, which is the reason why it is hard to breathe on high mountains without an artificial air supply and impossible to do so in the stratosphere or above it. At the upper edge of the mesosphere, Earth's gravitational field is no longer strong enough to hold large quantities of hydrogen, lightest of all elements, which constitutes the atmosphere at that point. Beyond the mesosphere, the atmosphere simply fades away, because there is not sufficient gravitational force to hold its particles in place.

Back down on Earth, gravity measurements are of great importance to the petroleum industry, which uses them to locate oil-containing salt domes. Furthermore, geologists, in general, remain acutely interested in measurements of gravity, the force behind tectonics, or the deformation of Earth's crust. Thus, gravity, responsible for fashioning Earth's exterior into the nearly spherical shape it has, is key to the shaping of its interior as well.

REAL-LIFE APPLICATIONS

Gravity on Earth

Using Newton's gravitational formula, it is relatively easy to calculate the pull of gravity between two objects. It is also easy to see why the attraction is insignificant unless at least one of the objects has enormous mass. In addition, application of the formula makes it clear why G is such a tiny number.

Suppose two people each have a mass of 45.5 kg—equal to 100 lb. on Earth, though not on the Moon, a matter that will be explained later in this essay—and they stand 1 m (3.28 ft.) apart. Thus, m_1m_2 is equal to 2,070 kg (4,555 lb.), and r^2 is equal to 1 m squared. Applied to the gravitational formula, this figure is rendered as 2,070 $kg^2/1$ m^2. This number then is multiplied by the gravitational constant, and the result is a net gravitational force of 0.000000138 N (0.00000003 lb.)—about the weight of a single-cell organism!

WEIGHT. What about Earth's gravitational force on one of those people? To calculate this force, we could apply the formula for universal gravitation, substituting Earth for m_2, especially because the mass of Earth is known: 5.98×10^{24} kg, or 5.98 septillion (1 followed by 24 zeroes) kg. We know the value of that mass, in fact, through the application of Newton's laws and the formulas derived from them. But for measuring the gravitational force between something as massive as Earth and something as small as a human body, it makes more sense to apply instead the formula embodied in Newton's second law of motion: $F = ma$. (Force equals mass multiplied by acceleration.)

For a body of any mass on Earth, acceleration is figured in terms of g—the acceleration due to gravity, which, as noted earlier, is equal to 32 ft. (9.8 m) per second squared. (Note, also, that this is a lowercase g, as opposed to the uppercase G that represents the gravitational constant.) Using the metric system, by multiplying the appropriate mass figure in kilograms by 9.8 m/s^2, one would obtain a value in newtons (N). To perform the same calculation with the English system, used in America, it would be necessary first to calculate the value of mass in slugs (which, needless to say, is a little-known unit) and multiply it by 32 $ft./s^2$ to yield a value in pounds.

In both cases, the value obtained, whether in newtons or pounds, is a measure of weight rather than of mass, which is measured in kilograms or slugs. For this reason, it is not entirely accurate to say that 1 kg is equal to 2.2 lb. This is true on Earth, but it would not be true on the Moon. The kilogram is a unit of mass, and as such it would not change anywhere in the universe, whereas the pound is a unit of force (in this case, gravitational force) and therefore varies according to the rate of acceleration for the gravitational field in which it is measured. For this reason, scientists prefer to use figures for mass, which is one of the fundamental properties (along with length, time, and electric charge) of the universe.

Why Earth Is Round—and Not Round

Everyone knows that Earth, the Sun, and all other large bodies in space are "round" (i.e., spherical), but why is that true? The reason is that gravity will not allow them to be otherwise: for any large object, the gravitational pull of its interior forces the surface to assume a relatively uniform shape. The most uniform of three-dimensional shape is that of a sphere, and the larger the mass of an object, the greater its tendency toward sphericity.

Earth has a relatively small vertical differential between its highest and lowest surface points, Mount Everest (29,028 ft., or 8,848 m) on the Nepal-Tibet border and the Mariana Trench (–36,198 ft., –10,911 m) in the Pacific Ocean, respectively. The difference is just 12.28 mi. (19.6 km)—not a great distance, considering that Earth's radius is about 4,000 mi. (6,400 km).

On the other hand, an object of less mass is more likely to retain a shape that is far less than spherical. This can be shown by reference to the Martian moons Phobos and Deimos, both of which are oblong—and both of which are tiny, in



The force of gravity imparts a spherical shape to Earth because of its large mass. An object of less mass will have a far less spherical shape. The Martian moon Phobos, shown here, is oblong owing to its tiny mass. *(© Julian Baum/Photo Researchers. Reproduced by permission.)*

terms of size and mass, compared with Earth's Moon. Mars itself has a radius half that of Earth, yet its mass is only about 10% of Earth's. In light of what has been said about mass, shape, and gravity, it should not be surprising to learn that Mars is also home to the tallest mountain in the solar system, the volcano Olympus Mons, which stands 16 mi. (27 km) high.

EARTH'S 'FLAT TOP' (AND BOTTOM). With regard to gravitation, a spherical object behaves as though its mass were concentrated near its center, and indeed, 33% of Earth's mass is at its core, even though the core accounts for only about 20% of the planet's volume. Geologists believe that the composition of Earth's core must be molten iron, which creates the planet's vast electromagnetic field.

It should be noted, however, that Earth is not really a perfect sphere, and the idea that its mass is concentrated at its center, while it works well in general, poses some problems in making exact gravitational measurements. If Earth were standing still, it would be much nearer to the shape of a sphere; however, it is not standing still but instead rotates on its axis, as does every other object of any significance in the solar system.

Incidentally, if Earth were suddenly to stop spinning, the gases in the atmosphere would keep moving at their current rate of about 1,000 MPH (1,600 km/h). They would sweep over the planet with the force of the greatest hurricane ever known, ripping up everything but the mountains. As to why Earth spins at all, scientists are not entirely sure. It may well be angular momentum (the momentum associated with rotational motion) imparted to it at some point in the very distant past, perhaps because it and the rest of the solar system were once part of a vast spinning cloud.

At any rate, the fact that Earth is spinning on its axis creates a certain centripetal, or inward-pulling, force, and this force produces a corresponding centrifugal (outward) component. To understand this concept, consider what happens to a sample of blood when it is rotated in a centrifuge. When the centrifuge spins, centripetal force pulls the material in the vial toward the center of the spin, but the material with greater mass has more inertia and therefore responds less to centripetal force. As a result, the heavier red blood cells tend to stay at the bottom of the vial (or, as it is spinning, on the outside), while the lighter plasma is pulled inward. The result is the separation between plasma and red blood cells.

Where Earth is concerned, this centrifugal component of centripetal force manifests as an equatorial bulging. Simply put, Earth's diameter around the equator is greater than at the poles, which are slightly flattened. The difference is small—the equatorial diameter of Earth is about 26.72 mi. (43 km) greater than the polar diameter—but it is not insignificant. In fact, as noted later, a person of fairly significant weight actually would notice a difference if he or she got on the scales at the equator (say, in Singapore) and then later weighed in near one of the poles (for instance, in the Norwegian possession of Svalbard, the northernmost human settlement on Earth).

Owing to this departure from a perfectly spherical shape, the Sun and Moon exert additional torques on Earth, and these torques cause shifts in the position of the planet's rotational axis in space. An imaginary line projected from

KEY TERMS

ACCELERATION: A change in velocity over time. The acceleration due to gravity, for instance, is 32 ft. (9.8 m) per second per second, meaning that for every second an object falls, its velocity is increasing as well.

ATMOSPHERE: In general, an atmosphere is a blanket of gases surrounding a planet. Unless otherwise identified, however, the term refers to the atmosphere of Earth, which consists of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon, which together comprise 0.07%.

CENTRIFUGAL: A term describing the tendency of objects in uniform circular motion to move outward, away from the center of the circle. Though the term centrifugal force often is used, it is inertia, rather than force, that causes the object to move outward.

CENTRIPETAL FORCE: The force that causes an object in uniform circular motion to move inward, toward the center of the circle.

FORCE: The product of mass multiplied by acceleration.

GEODESY: An area of geophysics devoted to the measurement of Earth's shape and gravitational field.

GEOID: A surface of uniform gravitational potential covering the entire Earth at a height equal to sea level.

GEOPHYSICS: A branch of the earth sciences that combines aspects of geology and physics. Geophysics addresses the planet's physical processes as well as its gravitational, magnetic, and electric properties and the means by which energy is transmitted through its interior.

INERTIA: The tendency of an object at rest to remain at rest or an object in motion to remain in motion, at a uniform velocity, at a uniform velocity, unless acted upon by some outside force.

MASS: A measure of inertia, indicating the resistance of an object to a change in its motion.

POTENTIAL: Position in a field, such as a gravitational force field.

SCIENTIFIC METHOD: A set of principles and procedures for systematic study that includes observation; the formation of hypotheses, theories, and laws; and continual testing and reexamination.

SCIENTIFIC REVOLUTION: A period of accelerated scientific discovery that completely reshaped the world. Usually dated from about 1550 to 1700, the Scientific Revolution saw the origination of the scientific method and the introduction of ideas such as the heliocentric (Sun-centered) universe and gravity.

TORQUE: A force that produces, or tends to produce, rotational motion.

UNIFORM CIRCULAR MOTION: The motion of an object around the center of a circle in such a manner that speed is constant or unchanging.

VACUUM: An area devoid of matter, even air.

VELOCITY: Speed in a certain direction.

WEIGHT: A measure of the gravitational force on an object. Weight thus would change from planet to planet, whereas mass remains constant throughout the universe. A pound is a unit of weight, whereas a kilogram is a unit of mass.

the North Pole and into space therefore, over a period of time, would appear to move. In the course of about 25,800 years, this point (known as the celestial north pole) describes the shape of a cone, a movement known as Earth's *precession.*

Satellites

Why, then, does Earth move around the Sun, or the Moon around Earth? As should be clear from Newton's gravitational formula and the third law of motion, the force of gravity works both ways: not only does a stone fall toward Earth, but Earth also actually falls *toward it.* The mass of Earth is so great compared with that of the stone that the movement of Earth is imperceptible—but it does happen.

Furthermore, because Earth is round, when one hurls a projectile at a great distance, Earth curves away from the projectile. Eventually, gravity itself forces the projectile to the ground. If one were to fire a rocket at 17,700 mi. per hour (28,500 km per hour), however, something unusual would happen. At every instant of time, the projectile would be falling toward Earth with the force of gravity—*but* the curved Earth would be falling away from it at the same rate. Hence, the projectile would remain in constant motion around the planet—that is, it would be in orbit.

The same is true of an artificial satellite's orbit around Earth: even as the satellite falls toward Earth, Earth falls away from it. Change the names of the players, and this same relationship exists between Earth and its great natural satellite, the Moon. Furthermore, it is the same with the Sun and *its* many satellites, including Earth: Earth plunges toward the Sun with every instant of its movement, but at every instant, the Sun falls away.

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GEOMAGNETISM

CONCEPT

Scientists have long recognized a connection between electricity and magnetism, but the specifics of this connection, along with the recognition that electromagnetism is one of the fundamental interactions in the universe, were worked out only in the mid–nineteenth century. By that time, geologists had come to an understanding of Earth as a giant magnet. This was the principle that made possible the operation of compasses, which greatly aided mariners in navigating the seas: magnetic materials, it so happened, point northward. As it turns out, however, Earth's magnetic North Pole is not the same as its geographic one, and even the pole's northerly location is not a permanent fact. Once upon a time and, in fact, at many times in Earth's history, the magnetic North Pole lay at the southern end of the planet.

HOW IT WORKS

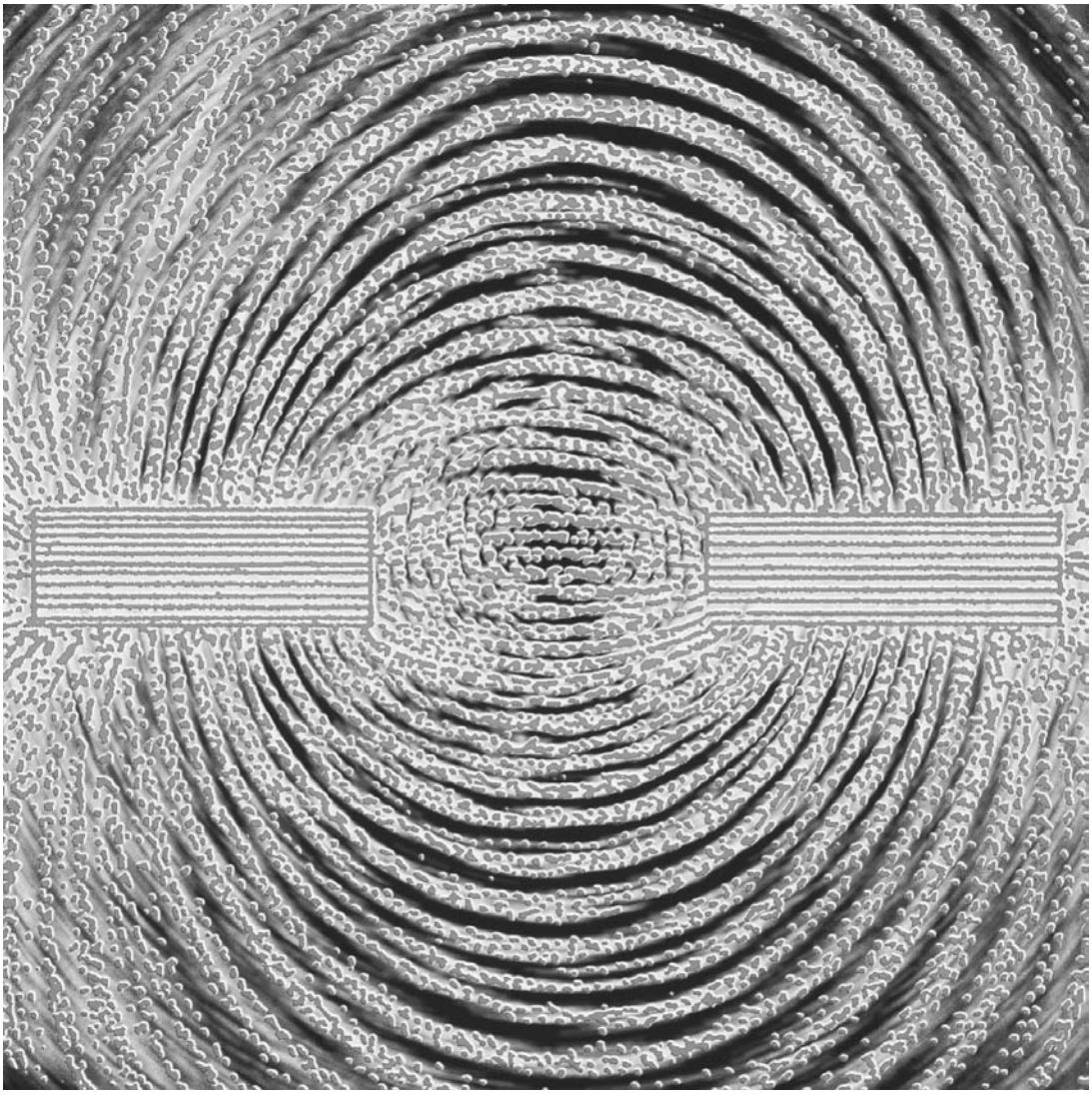
Electromagnetism

The Greek philosopher Thales (640?–546 B.C.) was the first to observe that when amber is rubbed with certain types of materials, the friction imparts to it the ability to pick up light objects. The word electricity comes from the Greek word for amber, *elektron,* and, in fact, magnetism and electricity are simply manifestations of the same force. This concept of electric and magnetic interaction seems to have been established early in human history, though it would be almost 2,500 years before scientists came to a mature understanding of the relationship.

As in so much else, studies in electromagnetism made little progress from the time of the Romans to the late Renaissance, a span of nearly 1,500 years. Yet it is worth noting that thefirst ideas scientists had about studying Earth's history scientifically came from observing the planet's magnetic field. In the course of his work on that subject, the English astronomer Henry Gellibrand (1597–1636) showed that the field has changed over time. This suggested that it would be possible to form hypotheses about the planet's past, even though humans had no direct information regarding the origins of Earth. Thus, Gellibrand (who, ironically, was also a minister) helped make it possible for geologists to move beyond a strict interpretation of the Bible in studying the history of Earth. (See Earth, Science, and Nonscience for more on the Genesis account and its interpretations.)

ELECTROMAGNETIC STUDIES COME OF AGE. Beginning in the 1700s, a number of thinkers conducted experiments concerning the nature of electricity and magnetism and the relationship between them. Among these thinkers were several giants in physics and other disciplines, including one of America's greatest founding fathers, Benjamin Franklin (1706–1790). In addition to his famous (and highly dangerous) experiment with lightning, Franklin also contributed the names positive and negative to the differing electric charges discovered earlier by the French physicist Charles Du Fay (1698–1739).

In 1785 the French physicist and inventor Charles Coulomb (1736–1806) established the basic laws of electrostatics and magnetism. He maintained that there is an attractive force that, like gravitation, can be explained in terms of the



The magnetic field around two bar magnets. *(© A. Pasieka/Photo Researchers. Reproduced by permission.)*

inverse of the square of the distance between objects (see Gravity and Geodesy). That attraction itself, however, results not from gravity but from electric charge, according to Coulomb.

A few years later, the German mathematician Karl Friedrich Gauss (1777–1855) developed a mathematical theory for finding the magnetic potential of any point on Earth. His contemporary, the Danish physicist Hans Christian Oersted (1777–1851), became the first scientist to establish a clear relationship between electricity and magnetism. This led to the formalization of electromagnetism, the branch of physics devoted to the study of electric and magnetic phenomena.

The French mathematician and physicist André Marie Ampère (1775–1836) concluded that magnetism is the result of electricity in motion, and in 1831 the British physicist and chemist Michael Faraday (1791–1867) published his theory of electromagnetic induction. This theory shows how an electric current in one coil can set up a current in another through the development of a magnetic field, and it enabled Faraday's development of the first generator. For the first time in history humans were able to convert mechanical energy systematically into electric energy.

ELECTROMAGNETIC FORCE. By this point scientists were convinced that a relationship between electricity and magnetism existed, yet they did not know exactly *how* the two related. Then, in 1865, the Scottish physicist James Clerk Maxwell (1831–1879) published a

groundbreaking paper, "On Faraday's Lines of Force," in which he outlined a theory of electromagnetic force. The latter may be defined as the total force on an electrically charged particle, which is a combination of forces due to electric and magnetic fields around the particle.

Maxwell thus had discovered a type of force in addition to gravity, and this reflected a "new" type of fundamental interaction, or a basic mode by which particles interact in nature. Nearly two centuries earlier Sir Isaac Newton (1642–1727) had identified the first, gravity, and in the twentieth century two other forms of fundamental interaction—strong nuclear and weak nuclear—were identified as well.

In his work Maxwell drew on the studies conducted by his predecessors but added a new statement. According to Maxwell, electric charge is conserved, meaning that the sum total of electric charge in the universe does not change, though it may be redistributed. This statement, which did not contradict any of the experimental work done by other physicists, was based on Maxwell's predictions regarding what should happen in situations of electromagnetism. Subsequent studies have supported his predictions.

Magnetism

What, then, is the difference between electricity and magnetism? It is primarily a matter of orientation. When two electric charges are at rest, it appears to an observer that the force between them is merely electric. If the charges are in motion relative to the observer, it appears as though a different sort of force, known as magnetism, exists between them.

An electromagnetic wave, such as that which is emitted by the Sun, carries both an electric and a magnetic component at mutually perpendicular angles. If you extend your hand, palm flat, with the fingers straight and the thumb pointing at a 90° angle to the fingers, the direction that the fingers are pointing would be that of the electromagnetic wave. Your thumb points in the direction of the electric field, and the flat of your palm indicates the direction of the magnetic field, which is perpendicular both to the electric field and to the direction of wave propagation.

A field, in this sense, is a region of space in which it is possible to define the physical properties of each point in the region at any given moment in time. Thus, an electric field and a magnetic field are simply regions in which the electric and magnetic components, respectively, of electromagnetic force are exerted.

MAGNETISM AT THE ATOMIC LEVEL. At the atomic level magnetism is the result of motion by electrons (negatively charged subatomic particles) in relation to one another. Rather like planets in a solar system, electrons revolve around the atom's nucleus and rotate on their own axes. (In fact, the exact nature of their movement is much more complex, but this analogy is accurate enough for the present purposes.) Both types of movement create a magnetic force field between electrons, and as a result the electron takes on the properties of a tiny bar magnet with a north pole and south pole. Surrounding this infinitesimal magnet are lines of magnetic force, which begin at the north pole and curve outward, describing an ellipse as they return to the south pole.

In most atoms, electrons are paired such that their magnetic fields cancel out one another. However, in certain cases, such as when there is an odd electron or when other factors become more significant, the fields line up to create what is known as a net magnetic dipole, or a unity of direction. These elements, among them, iron, cobalt, and nickel as well as various alloys or mixtures, are commonly known as magnetic metals, or natural magnets.

MAGNETIZATION. Magnetization occurs when an object is placed in a magnetic field. In this field magnetic force acts on a moving charged particle such that the particle would experience no force if it moved in the direction of the magnetic field. In other words, it would be "drawn," as a ten-penny nail is drawn to a common bar or horseshoe (U-shaped) magnet. An electric current is an example of a moving charge, and, indeed, one of the best ways to create a magnetic field is with a current. Often this is done by means of a solenoid, a current-carrying wire coil through which the material to be magnetized is passed, much as one would pass a straight wire up through the interior of a spring.

When a natural magnet becomes magnetized (that is, when a magnetic metal or alloy comes into contact with an external magnetic field), a change occurs at the level of the domain, a group of atoms equal in size to about 5×10^{-5} meters across—just large enough to be visible under a microscope.

In an unmagnetized sample, there may be an alignment of unpaired electron spins within a domain, but the direction of the various domains' magnetic forces in relation to one another is random. Once a natural magnet is placed within an external magnetic force field, however, one of two things happens to the domains. Either they all come into alignment with the field or, in certain types of material, those domains in alignment with the field grow, while the others shrink to nonexistence.

The first of these processes is called domain alignment, or ferromagnetism, and the second is termed domain growth, or ferrimagnetism. Both processes turn a natural magnet into what is known as a permanent magnet—or, more simply, a magnet. The magnet is then capable of temporarily magnetizing a ferromagnetic item, as, for instance, when one rubs a paper clip against a permanent magnet and then uses the magnetized clip to lift other paper clips. Of the two varieties, however, a ferromagnet is stronger, because it requires a more powerful magnetic force field to become magnetized. Most powerful of all is a saturated ferromagnetic metal, one in which all the unpaired electron spins are aligned.

REAL-LIFE APPLICATIONS

The Magnetic Compass

A bar magnet placed in a magnetic field will rotate until it lines up with the field's direction. The same thing happens when one suspends a magnet from a string: it lines up with Earth's magnetic field and points in a north-south direction. The Chinese of the first century B.C. discovered that a strip of magnetic metal always tends to point toward geographic north, though they were unaware of the electromagnetic force that causes this to happen.

This led ultimately to the development of the magnetic compass, which typically consists of a magnetized iron needle suspended over a card marked with the four cardinal directions (north, south, east, and west). The needle is attached to a pivoting mechanism at its center, which allows it to move freely so that the tip of the needle will always point the user northward. The magnetic compass proved so important that it typically is ranked alongside paper, printing, and gunpowder as one of premodern China's four great gifts to the West. Before the compass, mariners had to depend purely on the position of the Sun and other, less reliable means of determining direction; hence, the invention quite literally helped open up the world.

ODD BEHAVIOR OF THE COMPASS. The compass, in fact, helped make possible the historic voyage of Christopher Columbus (1451–1506) in 1492. While sailing across the Atlantic, Columbus noticed something odd: his compass did not always point toward what he knew, based on the Sun's position, to be geographic north. The further he traveled, the more he noticed this phenomenon, which came to be known as magnetic declination.

When Columbus returned to Europe and reported on his observations of magnetic declination (along with the much bigger news of his landing in the New World, which he thought was Asia), his story perplexed mariners. Eventually, European scientists worked out tables of magnetic declination, showing the amount of deviation at various points on Earth, and this seemed to allay sailors' concerns.

Then, in 1544, the German astronomer Georg Hartmann (1489–1564) observed that a freely floating magnetized needle did not always stay perfectly horizontal and actually dipped more and more strongly as he traveled north. When he was moving south, on the other hand, the needle tended to become more closely horizontal. For many years, this phenomenon, along with magnetic declination, remained perplexing. Nor, for that matter, did scientists understand exactly how or why a compass works. Then, in 1600, the English physicist William Gilbert (1540–1603) became the first to suggest a reason.

Earth as a Giant Magnet

Gilbert coined the terms electric attraction, electric force, and magnetic pole. In De magnete (On the magnet), he became the first thinker to introduce the idea, now commonly accepted, that Earth itself is a giant magnet. Not only does it have north and south magnetic poles, but it also is surrounded by vast arcs of magnetic force, called the geomagnetic field. (The term geomagnetism, as opposed to magnetism, refers to the magnetic properties of Earth as a whole rather

than those possessed by a single object or place on Earth.)

In the paragraphs that follow, we discuss the shape of this magnetic field, including the positions of the magnetic north and south poles; the origins of the field, primarily in terms of the known or suspected physical forces that sustain it (as opposed to the original cause of Earth's magnetic field, a more complicated and speculative subject); as well as changes in the magnetic field. Those changes, along with techniques for measuring the geomagnetic field, also are discussed at other places in this book.

EARTH'S MAGNETIC FIELD. Hartmann's compass phenomenon can be explained by the fact that Earth is a magnet and that its north and south magnetic poles are close to the geographic north and south. As for the phenomenon observed by Columbus, it is a result of the difference between magnetic and geographic north. If one continued to follow a compass northward, it would lead not to Earth's North Pole but to a point identified in 1984 as 77°N, 102°18' W—that is, in the Queen Elizabeth Islands of far northern Canada.

Earlier we described the lines that make up the magnetic force field around a bar magnet. A field of similar shape, though, of course, of much larger size (yet still invisible), also surrounds Earth. From the magnetic north and south poles, lines of magnetic force rise into space and form giant curves that come back around and reenter Earth at the opposing pole, so that the planet is surrounded by a vast series of concentric loops. If one could draw a straight line through the center of all these loops, it would reach Earth at a point 11° from the equator. Likewise the north and south magnetic poles—which are on a plane perpendicular to that of Earth's magnetic field—are 11° off the planet's axis.

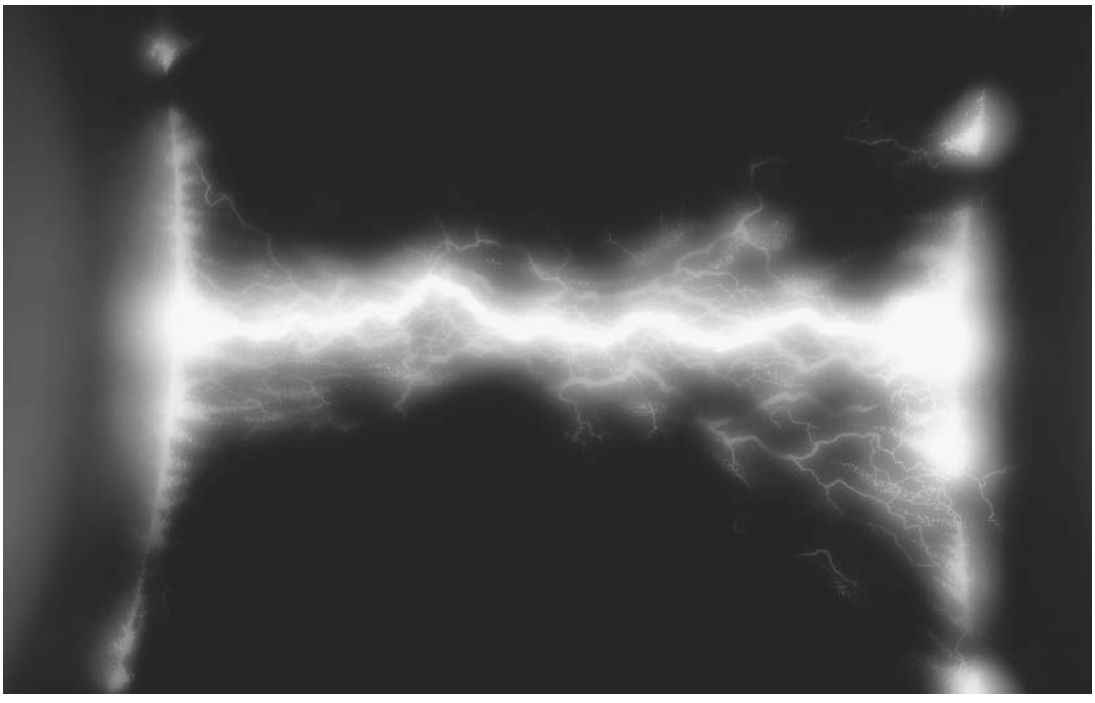
THE MAGNETOSPHERE. Surrounding the planet is a vast region called the magnetosphere, an area in which ionized particles (i.e., ones that have lost or gained electrons so as to acquire a net electric charge) are affected by Earth's magnetic field. The magnetosphere is formed by the interaction between our planet's magnetic field and the solar wind, a stream of particles from the Sun. (See Sun, Moon, and Earth for more about the solar wind.) Its shape would be akin to that of Earth's magnetic field, as described earlier, were it not for the Sun's influence.

The side of the magnetosphere closer to the Sun does indeed resemble the giant series of concentric loops described earlier. These loops are enormous, such that the forward, or sunlit, edge of the magnetosphere is located at a distance of some 10 Earth radii (about 35,000 mi., or 65,000 km). On the other side from the Sun—the rear, or dark, side—the shape of the magnetosphere is quite different. Instead of forming relatively small loops that curve right back around into Earth's poles, the lines of magnetic force on this side shoot straight out into space a distance of some 40 Earth radii (about 140,000 mi., or 260,000 km).

The shape of the magnetosphere, then, is a bit like that of a comet moving toward the Sun. Surrounding it is the magnetopause, a sort of magnetic dead zone about 62 mi. (100 km) thick, which shields Earth from most of the solar wind. In front of it (toward the Sun) is an area of magnetic turbulence known as the magnetosheath, and still closer to the Sun is a boundary called the bow shock, a shock-wave front that slows particles of solar wind considerably. Since Earth is turning, the side of the planet away from the Sun is continually changing, of course, but the shape of the magnetosphere remains more or less intact. It is, however, highly affected by solar activity, such that an increase in solar wind can cause a depression in the magnetosphere. (See Sun, Moon, and Earth for a discussion of auroras, produced by an interaction between the solar wind and the magnetosphere.)

The Source of Earth's Magnetic Field

As noted earlier, scientists at present understand little with regard to the *origins* of Earth's magnetic field—that is, the original action or actions that resulted in the creation of a geomagnetic field that has remained active for billions of years. No less a figure than Albert Einstein (1879–1955) identified this question as one of the great unsolved problems of science. On the other hand, scientists do have a good understanding of the geomagnetic field's *source,* in terms of the physical conditions that make it possible. (This distinction is rather like that between efficient cause and material cause, as discussed in Earth, Science, and Nonscience.)



The electric discharge between two metal objects. *(© P. Jude/Photo Researchers. Reproduced by permission.)*

It is believed that the source of Earth's magnetism lies in a core of molten iron some 4,320 mi. (6,940 km) across, constituting half the planet's diameter. Within this core run powerful electric currents that create the geomagnetic field. Actually, the field seems to originate in the outer core, consisting of an iron-nickel alloy that is kept fluid owing to the exceedingly great temperatures. The materials of the outer core undergo convection, vertical circulation that results from variations in density brought about by differences in temperature.

This process of convection (imagine giant spirals moving vertically through the molten metal) creates the equivalent of a solenoid, described earlier. Even so, there had to be an original source for the magnetic field, and it is possible that it came from the Sun. In any case, the magnetic field could not continue to exist if the fluid of the outer core were not in constant convective motion. If this convection stopped, within about 10,000 years (which, in terms of Earth's life span, is like a few seconds to a human being), the geomagnetic field would decay and cease to operate. Likewise, if Earth's core ever cooled and solidified, Earth would become like the Moon, a body whose magnetic field has disappeared, leaving only the faintest traces of magnetism in its rocks.

Changes in the Magnetic Field

Though there is no reason to believe that anything so dramatic will happen, there are curious and perhaps troubling signs that Earth's magnetic field is changing. According to data recorded by the U.S. Geological Survey, which updates information on magnetic declination, the field is shifting—and weakening. Over the course of about a century, scientists have recorded data suggesting a reduction of about 6% in the strength of the magnetic field.

The behavior, in terms of both weakening and movement, appears to be similar to changes taking place in the magnetic field of the Sun. Indeed, as we have seen already, Earth's magnetism is heavily affected by the Sun, and it is possible that a period of strong solar-flare activity could shut down Earth's magnetic field. Even the present trend of weakening, if it were to continue for just 1,500 years, would wipe out the magnetic field. Some scientists believe that the planet is simply experiencing a fluctuation, however, and that the geomagnetic field will recover. Others

KEY TERMS

CONSERVATION: In physics and other sciences, "to conserve" something means "to result in no net loss of" that particular component. It is possible that within a given system the component may change form or position, but as long as the net value of the component remains the same, it has been conserved.

DIPOLE: A pair of equal and opposite electric charges, or an entire body having the characteristics of a dipole—for instance, a magnet with north and south poles.

ELECTROMAGNETIC ENERGY: A form of energy with electric and magnetic components that travels in waves.

ELECTROMAGNETIC FORCE: The total force on an electrically charged particle, which is a combination of forces due to electric and magnetic fields around the particle. Electromagnetic force reflects electromagnetic interaction, one of the four fundamental interactions in nature.

ELECTRON: A negatively charged particle in an atom, which spins around the nucleus.

ELEMENT: A substance made up of only one kind of atom. Unlike compounds, elements cannot be broken chemically into other substances.

FIELD: A region of space in which it is possible to define the physical properties of each point in the region at any given moment in time.

FUNDAMENTAL INTERACTION: The basic mode by which particles interact. There are four known fundamental interactions in nature: gravitational, electromagnetic, strong nuclear, and weak nuclear.

GEOMAGNETISM: A term referring to the magnetic properties of Earth as a whole rather than those possessed by a single object or place on Earth.

MAGNETIC DECLINATION: The angle between magnetic north and geographic north.

MAGNETOSPHERE: An area surrounding Earth, reaching far beyond the atmosphere, in which ionized particles (i.e., ones that have lost or gained electrons so as to acquire a net electric charge) are affected by Earth's magnetic field.

PALEOMAGNETISM: An area of historical geology devoted to studying the direction and intensity of magnetic fields in the past, as discerned from the residual magnetization of rocks.

POTENTIAL: Position in a field, such as a gravitational force field.

SOLAR WIND: A stream of particles continually emanating from the Sun and moving outward through the solar system.

SYSTEM: Any set of interactions that can be set apart mentally from the rest of the universe for the purposes of study, observation, and measurement.

maintain that the geomagnetic field is on its way to a reversal.

A reversal? Odd as it may sound, the direction of the geomagnetic field has reversed itself many, many times in the past. Furthermore, the planet has attempted unsuccessfully to reverse its geomagnetic field many more times—as recently as 30,000 to 40,000 years ago. These reversals are among the interests of paleomagnetism, the area of geology devoted to the direction and intensity of magnetic fields in the past, as discerned from the residual magnetization of rocks.

A compass works, of course, because the metal points toward Earth's magnetic north pole, which is close to its geographic north pole. Likewise, the magnetic materials in the rocks of Earth point north—or rather, they *would* point north if the direction of the magnetic field had not changed over time. Around the turn of the nineteenth century, geologists noticed that whereas some magnetic rocks pointed toward Earth's current North Pole, some were pointing in the opposite direction. This led to the realization that the magnetic field had reversed and to the development of paleomagnetism as a field of study. Studies in paleomagnetism, in turn, have provided confirmation of the powerful theory known as plate tectonics. (See Plate Tectonics for more on paleomagnetism and the shifting of plates beneath Earth's surface.)

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CONVECTION

CONCEPT

Convection is the name for a means of heat transfer, as distinguished from conduction and radiation. It is also a term that describes processes affecting the atmosphere, waters, and solid earth. In the atmosphere, hot air rises on convection currents, circulating and creating clouds and winds. Likewise, convection in the hydrosphere circulates water, keeping the temperature gradients of the oceans stable. The term convection generally refers to the movement of fluids, meaning liquids and gases, but in the earth sciences, convection also can be used to describe processes that occur in the solid earth. This geologic convection, as it is known, drives the plate movement that is one of the key aspects of plate tectonics.

HOW IT WORKS

Introduction to Convection

Some concepts and phenomena cross disciplinary boundaries within the earth sciences, an example being the physical process of convection. It is of equal relevance to scientists working in the geologic, atmospheric, and hydrologic sciences, or the realms of study concerned with the geosphere, atmosphere, and hydrosphere, respectively. The only major component of the earth system not directly affected by convection is the biosphere, but given the high degree of interconnection between different subsystems, convection indirectly affects the biosphere in the air, waters, and solid earth.

Convection can be defined as vertical circulation that results from differences in density ultimately brought about by differences in temperature, and it involves the transfer of heat through the motion of hot fluid from one place to another. In the physical sciences, the term fluid refers to any substance that flows and therefore has no definite shape. This usually means liquids and gases, but in the earth sciences it can refer even to slow-flowing solids. Over the great expanses of time studied by earth scientists, the net flow of solids in certain circumstances (for example, ice in glaciers) can be substantial.

Convection and Heat

As indicated in the preceding paragraph, convection is related closely to heat and temperature and indirectly related to another phenomenon, thermal energy. What people normally call *heat* is actually thermal energy, or kinetic energy (the energy associated with movement) produced by molecules in motion relative to one another.

Heat, in its scientific meaning, is internal thermal energy that flows from one body of matter to another or from a system at a higher temperature to a system at a lower temperature. Temperature thus can be defined as a measure of the average molecular kinetic energy of a system. Temperature also governs the direction of internal energy flow between two systems. Two systems at the same temperature are said to be in a state of thermal equilibrium; when this occurs, there is no exchange of heat, and therefore heat exists only in transfer between two systems.

There is no such thing as cold, only the absence of heat. If heat exists only in transit between systems, it follows that the direction of heat flow must *always* be from a system at a higher temperature to a system at a lower tempera-

ture. (This fact is embodied in the second law of thermodynamics, which is discussed, along with other topics mentioned here, in Energy and Earth.) Heat transfer occurs through three means: conduction, convection, and radiation.

Conduction and radiation. Conduction involves successive molecular collisions and the transfer of heat between two bodies in contact. It usually occurs in a solid. Convection requires the motion of fluid from one place to another, and, as we have noted, it can take place in a liquid, a gas, or a near solid that behaves like a slow-flowing fluid. Finally, radiation involves electromagnetic waves and requires no physical medium, such as water or air, for the transfer.

If you put one end of a metal rod in a fire and then touch the "cool" end a few minutes later, you will find that it is no longer cool. This is an example of heating by conduction, whereby kinetic energy is passed from molecule to molecule in the same way as a secret is passed from one person to another along a line of people standing shoulder to shoulder. Just as the original phrasing of the secret becomes garbled, some kinetic energy is inevitably lost in the series of transfers, which is why the end of the rod outside the fire is still much cooler than the one sitting in the flames.

As for radiation, it is distinguished from conduction and convection by virtue of the fact that it requires no medium for its transfer. This explains why space is cold yet the Sun's rays warm Earth: the rays are a form of electromagnetic energy, and they travel by means of radiation through space. Space, of course, is the virtual absence of a medium, but upon entering Earth's atmosphere, the heat from the electromagnetic rays is transferred to various media in the atmosphere, hydrosphere, geosphere, and biosphere. That heat then is transferred by means of convection and conduction.

Heat transfer through convection. Like conduction and unlike radiation, convection requires a medium. However, in conduction the heat is transferred from one molecule to another, whereas in convection the heated fluid itself is actually moving. As it does, it removes or displaces cold air in its path. The flow of heated fluid in this situation is called a convection current.

Convection is of two types: natural and forced. Heated air rising is an example of natural convection. Hot air has a lower density than that of the cooler air in the atmosphere above it and therefore is buoyant; as it rises, however, it loses energy and cools. This cooled air, now denser than the air around it, sinks again, creating a repeating cycle that generates wind.

Forced convection occurs when a pump or other mechanism moves the heated fluid. Examples of forced-convection apparatuses include some types of ovens and even refrigerators or air conditioners. As noted earlier, it is possible to transfer heat only from a high-temperature reservoir to a low-temperature one, and thus these cooling machines work by removing hot air. The refrigerator pulls heat from its compartment and expels it to the surrounding room, while an air conditioner pulls heat from a room or building and releases it to the outside.

Forced convection does not necessarily involve man-made machines: the human heart is a pump, and blood carries excess heat generated by the body to the skin. The heat passes through the skin by means of conduction, and at the surface of the skin it is removed from the body in a number of ways, primarily by the cooling evaporation of perspiration.

Real-Life Applications

Convective Cells

One important mechanism of convection, whether in the air, water, or even the solid earth, is the convective cell, sometimes known as the convection cell. The latter may be defined as the circular pattern created by the rising of warmed fluid and the sinking of cooled fluid. Convective cells may be only a few millimeters across, or they may be larger than Earth itself.

These cells can be observed on a number of scales. Inside a bowl of soup, heated fluid rises, and cooled fluid drops. These processes are usually hard to see unless the dish in question happens to be one such as Japanese miso soup. In this case, pieces of soybean paste, or miso, can be observed as they rise when heated and then drop down into the interior to be heated again.

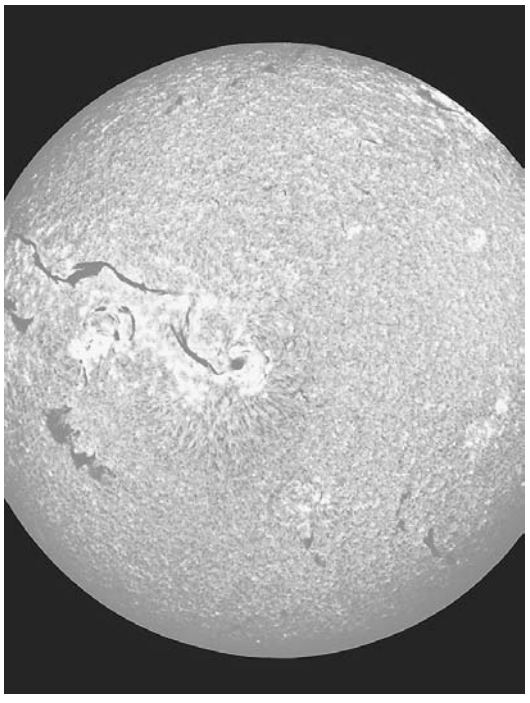
On a vastly greater scale, convective cells are present in the Sun. These vast cells appear on the Sun's surface as a grainy pattern formed by the



A cumulonimbus cloud—thunderhead—is a dramatic example of a convection cell. *(© Keith Kent/Photo Researchers. Reproduced by permission.)*

variations in temperature between the parts of the cell. The bright spots are the top of rising convection currents, while the dark areas are cooled gas on its way to the solar interior, where it will be heated and rise again.

A cumulonimbus cloud, or "thunderhead," is a particularly dramatic example of a convection cell. These are some of the most striking cloud formations one ever sees, and for this reason the director Akira Kurosawa used scenes of



Convective cells appear on the Sun's surface as a grainy pattern formed by variations in temperature. *(© Noao/Photo Researchers. Reproduced by permission.)*

rolling thunderheads to add an atmospheric quality (quite literally) to his 1985 epic *Ran.* In the course of just a few minutes, these vertical towers of cloud form as warmed, moist air rises, then cools and falls. The result is a cloud that seems to embody both power and restlessness, hence Kurosawa's use of cumulonimbus clouds in a scene that takes place on the eve of a battle.

A sea breeze. Convective cells, along with convection currents, help explain why there is usually a breeze at the beach. At the seaside, of course, there is a land surface and a water surface, both exposed to the Sun's light. Under such exposure, the temperature of land rises more quickly than that of water. The reason is that water has an extraordinarily high specific heat capacity—that is, the amount of heat that must be added to or removed from a unit of mass for a given substance to change its temperature by 33.8°F (1°C). Thus a lake, stream, or ocean is always a good place to cool down on a hot summer day.

The land, then, tends to heat up more quickly, as does the air above it. This heated air rises in a convection current, but as it rises and thus overcomes the pull of gravity, it expends energy and therefore begins to cool. The cooled air then sinks. And so it goes, with the heated air rising and the cooling air sinking, forming a convective cell that continually circulates air, creating a breeze.

Convective cells under our feet. Convective cells also can exist in the solid earth, where they cause the plates (movable segments) of the lithosphere—the upper layer of Earth's interior, including the crust and the brittle portion at the top of the mantle—to shift. They thus play a role in plate tectonics, one of the most important areas of study in the earth sciences. Plate tectonics explains a variety of phenomena, ranging from continental drift to earthquakes and volcanoes. (See Plate Tectonics for much more on this subject.)

Whereas the Sun's electromagnetic energy is the source of heat behind atmospheric convection, the energy that drives geologic convection is geothermal, rising up from Earth's core as a result of radioactive decay. (See Energy and Earth.) The convective cells form in the asthenosphere, a region of extremely high pressure at a depth of about 60–215 mi. (about 100–350 km), where rocks are deformed by enormous stresses.

In the asthenosphere, heated material rises in a convection current until it hits the bottom of the lithosphere (the upper layer of Earth's interior, comprising the crust and the top of the mantle), beyond which it cannot rise. Therefore it begins moving laterally or horizontally, and as it does so, it drags part of the lithosphere. At the same time, this heated material pushes away cooler, denser material in its path. The cooler material sinks lower into the mantle (the thick, dense layer of rock, approximately 1,429 mi. [2,300 km] thick, between Earth's crust and core) until it heats again and ultimately rises up, thus propagating the cycle.

Subsidence: Fair Weather and Foul

As with convective cells, subsidence can occur in the atmosphere or geosphere. The term subsidence can refer either to the process of subsiding, on the part of air or solid earth, or, in the case of solid earth, to the resulting formation. It thus is defined variously as the downward movement of air, the sinking of ground, or a depression in the earth. In the present context we will discuss atmospheric subsidence, which is more closely related to convection. (For more about geologic

KEY TERMS

ASTHENOSPHERE: A region of extremely high pressure underlying the lithosphere, where rocks are deformed by enormous stresses. The asthenosphere lies at a depth of about 60–215 mi. (about 100–350 km).

ATMOSPHERE: In general, an atmosphere is a blanket of gases surrounding a planet. Unless otherwise identified, however, the term refers to the atmosphere of Earth, which consists of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon, which together comprise 0.07%.

BIOSPHERE: A combination of all living things on Earth—plants, animals, birds, marine life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

CONDUCTION: The transfer of heat by successive molecular collisions. Conduction is the principal means of heat transfer in solids, particularly metals.

CONVECTION: Vertical circulation that results from differences in density ultimately brought about by differences in temperature. Convection involves the transfer of heat through the motion of hot fluid from one place to another and is of two types, natural and forced. (See *natural convection, forced convection.*)

CONVECTION CURRENT: The flow of material heated by means of convection.

CONVECTIVE CELL: The circular pattern created by the rising of warmed fluid and the sinking of cooled fluid. This is sometimes called a convection cell.

CORE: The center of Earth, an area constituting about 16% of the planet's volume and 32% of its mass. Made primarily of iron and another, lighter element (possibly sulfur), it is divided between a solid inner core with a radius of about 760 mi. (1,220 km) and a liquid outer core about 1,750 mi. (2,820 km) thick.

CRUST: The uppermost division of the solid earth, representing less than 1% of its volume and varying in depth from 3 to 37 mi. (5 to 60 km). Below the crust is the mantle.

FLUID: In the physical sciences, the term fluid refers to any substance that flows and therefore has no definite shape. Fluids can be both liquids and gases. In the earth sciences, occasionally substances that appear to be solid (for example, ice in glaciers) are, in fact, flowing slowly.

FORCED CONVECTION: Convection that results from the action of a pump or other mechanism (whether man-made or natural), directing heated fluid toward a particular destination.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

HEAT: Internal thermal energy that flows from one body of matter to another.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

KINETIC ENERGY: The energy that an object possesses by virtue of its motion.

KEY TERMS CONTINUED

LITHOSPHERE: The upper layer of Earth's interior, including the crust and the brittle portion at the top of the mantle.

MANTLE: The dense layer of rock, approximately 1,429 mi. (2,300 km) thick, between Earth's crust and its core.

NATURAL CONVECTION: Convection that results from the buoyancy of heated fluid, which causes it to rise.

PLATE TECTONICS: The name both of a theory and of a specialization of tectonics. As an area of study, plate tectonics deals with the large features of the lithosphere and the forces that shape them. As a theory, it explains the processes that have shaped Earth in terms of plates and their movement.

PLATES: Large, movable segments of the lithosphere.

RADIATION: The transfer of energy by means of electromagnetic waves, which require no physical medium (for example, water or air) for the transfer. Earth receives the Sun's energy via the electromagnetic spectrum by means of radiation.

SUBSIDENCE: A term that refers either to the process of subsiding, on the part of air or solid Earth, or, in the case of solid Earth, to the resulting formation. Subsidence thus is defined variously as the downward movement of air, the sinking of ground, or a depression in Earth's crust.

SYSTEM: Any set of interactions that can be set apart mentally from the rest of the universe for the purposes of study, observation, and measurement.

TECTONICS: The study of tectonism, including its causes and effects, most notably mountain building.

TECTONISM: The deformation of the lithosphere.

TEMPERATURE: The direction of internal energy flow between two systems when heat is being transferred. Temperature measures the average molecular kinetic energy in transit between those systems.

THERMAL ENERGY: Heat energy, a form of kinetic energy produced by the motion of atomic or molecular particles in relation to one another. The greater the relative motion of these particles, the greater the thermal energy.

subsidence, see the entries Geomorphology and Mass Wasting.)

In the atmosphere, subsidence results from a disturbance in the normal upward flow of convection currents. These currents may act to set up a convective cell, as we have seen, resulting in the flow of breeze. The water vapor in the air may condense as it cools, changing state to a liquid and forming clouds. Convection can create an area of low pressure, accompanied by converging winds, near Earth's surface, a phenomenon known as a cyclone. On the other hand, if subsidence occurs, it results in the creation of a high-pressure area known as an anticyclone.

Air parcels continue to rise in convective currents until the density of their upper portion is equal to that of the surrounding atmosphere, at which point the column of air stabilizes. On the other hand, subsidence may occur if air at an altitude of several thousand feet becomes denser than the surrounding air without necessarily being cooler or moister. In fact, this air is unusually dry, and it may be warm or cold. Its density then makes it sink, and, as it does, it compresses

the air around it. The result is high pressure at the surface and diverging winds just above the surface.

The form of atmospheric subsidence described here produces pleasant results, explaining why high-pressure systems usually are associated with fair weather. On the other hand, if the subsiding air settles onto a cooler lay of air, it creates what is known as a subsidence inversion, and the results are much less beneficial. In this situation a warm air layer becomes trapped between cooler layers above and below it, at a height of several hundred or even several thousand feet. This means that air pollution is trapped as well, creating a potential health hazard. Subsidence inversions occur most often in the far north during the winter and in the eastern United States during the late summer.

WHEN A NON-FLUID ACTS LIKE A FLUID

Up to this point we have spoken primarily of convection in the atmosphere and the geosphere, but it is of importance also in the oceans. The miso soup example given earlier illustrates the movement of fluid, and hence of particles, that can occur when a convective cell is set up in a liquid.

Likewise, in the ocean convection—driven both by heat from the surface and, to a greater extent, by geothermal energy at the bottom—keeps the waters in constant circulation. Oceanic convection results in the transfer of heat throughout the depths and keeps the ocean stably stratified. In other words, the strata, or layers, corresponding to various temperature levels are kept stable and do not wildly fluctuate.

Ocean waters fit the most common, everyday definition of fluid, but as noted at the beginning of this essay, a fluid can be anything that flows—including a gas or, in special circumstances, a solid. Solid rocks or solid ice, in the form of glaciers, can be made to flow if the materials are deformed sufficiently. This occurs, for instance, when the weight of a glacier deforms ice at the bottom, thus causing the glacier as a whole to move. Likewise, geothermal energy can heat rock and cause it to flow, setting into motion the convective process of plate tectonics, described earlier, which literally moves the earth.

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ENERGY AND EARTH

CONCEPT

Earth is a vast flow-through system for the input and output of energy. The overwhelming majority of the input to Earth's energy budget comes from the Sun in the form of solar radiation, with geothermal and tidal energy rounding out the picture. Each form of energy is converted into heat and re-radiated to space, but the radiation that leaves Earth travels in longer wavelengths than that which entered the planet. This is in accordance with the second law of thermodynamics, which shows that energy output will always be smaller than energy input and that energy which flows through a system will return to the environment in a degraded form. Yet what the Earth system does in processing that energy, particularly the portion that passes through the biosphere, is amazing. Some biological matter decays and, over the course of several hundred million years, produces fossil fuels that have given Earth a slight energy surplus. Human use of fossil fuels is rapidly depleting those sources, however, while posing new environmental problems, and this has encouraged the search for alternative forms of energy. Many of those forms, most notably geothermal energy, come from Earth itself.

HOW IT WORKS

Energy, Work, and Power

Physicists define energy as the ability of an object (and in some cases a nonobject, such as a magnetic force field) to accomplish work. "Work" in this context does not have the same meaning as it does in everyday life; along with the closely related concept of power, it is defined very specifically in a scientific context.

Work is the exertion of force over a given distance, and therefore it is measured in units of force multiplied by units of length. In the English system used by most Americans, a pound is the unit of force, and the foot-pound (ft-lb) would be the unit of work. However, scientists worldwide use SI, or the International System, which applies metric units. The metric unit of force is the newton (N), and the metric unit of work is the joule (J), equal to 1 newton-meter (N × m).

Power is the rate at which work is accomplished over time and therefore is measured in units of work divided by units of time. The metric unit of power is the watt (W), named after James Watt (1736–1819), the Scottish inventor who developed the first fully viable steam engine and thus helped inaugurate the Industrial Revolution. A watt is equal to 1 J per second, but this is such a small unit that kilowatts, or units of 1,000 W, are more frequently used. Discussing the vast energy budget of Earth itself, however, requires use of an even larger unit: the terawatt (TW), equal to 10^{12} (one trillion) W.

Ironically, Watt himself—like most people in the British Isles and America—lived in a world that used the British system, in which the unit of power is the foot-pound per second. The latter unit, too, is very small, so for measuring the power of his steam engine, Watt suggested a unit based on something quite familiar to the people of his time: the power of a horse. One horsepower (hp) is equal to 550 ft-lb per second.

In the present context, we will rely as much as possible on SI units, especially because the watt is widely used in America. Horsepower typ-

ically is applied in the United States only for measuring the power of a mechanical device, such as an automobile or even a garbage disposal. For measuring electrical power, particularly in larger quantities, the SI kilowatt (kW) is used. When an electric utility performs a meter reading on a family's power usage, for instance, it measures that usage in terms of electrical "work" performed for the family and thus bills them by the kilowatt-hour (kWh).

Varieties of Energy

In the most fundamental sense, there are only three kinds of energy: kinetic, potential, and mass, or rest, energy. These types are, respectively, the energy an object possesses by virtue of its motion, its position (or its ability to perform work), and its mass. The first two are understood in relation to each other: for example, a ball held over the side of a building has a certain gravitational potential energy, but once it is dropped, it begins to lose potential energy and gain kinetic energy. The faster it moves, the greater the kinetic energy; but as it covers more distance, the less its potential energy is. (See Earth Systems for more about the kinetic-potential energy system.)

As Earth moves around the Sun, the gravitational interaction between the two bodies is not unlike that of the baseball and the ground in the illustration just given. Earth makes an elliptical, or oval-shaped, path in its orbit, meaning that the distance between it and the Sun is not uniform. At its furthest distance, Earth's potential energy is maximized, but as it comes closer to the Sun in its orbital path, its kinetic energy increases, with a corresponding decrease of potential energy.

MASS AND ENERGY. Mass, or rest, energy is identified in the famous formula $E = mc^2$, derived by Albert Einstein (1879–1955). In simple terms Einstein's formula means that every object possesses an amount of energy equal to its mass multiplied by the speed of light squared. Given that light travels at 186,000 mi. (299,339 km) per second, this is an enormous figure, even for a small object. A mere baseball, which weighs about 0.333 lb. (0.15 kg), possesses enough energy to yield about 3.75 billion kWh worth of power—enough to run all the lights and appliances in a typical American home for more than 156,000 years!

To release this energy in significant quantities, it would be necessary to accelerate the baseball to a speed close to that of light. Even in ordinary experience, however, very small amounts of mass are converted to energy. For instance, when a fire burns, the mass of the ashes combined with that of the particles and gases sent into the atmosphere is smaller (by an almost imperceptible fraction) than the mass of the original wood. The "lost" mass is converted to energy. These mass-energy conversions occur on a much larger level in nuclear reactions, such as the nuclear fusion of hydrogen atoms to form helium in the solar core (see Sun, Moon, and Earth).

MANIFESTATIONS OF ENERGY. In discussing kinetic and potential energy, the example of dropping a baseball from a height illustrates these two types of energy in a gravitational field—that is, the gravitational field of Earth. Yet the concept of potential and kinetic energy translates to a situation involving an electromagnetic field as well. For instance, the positive or negative attraction between two electromagnetically charged particles is analogous to the force of gravity, and a system of two or more charges possesses a certain amount of kinetic and potential electromagnetic energy.

Electromagnetic energy, which is the form in which solar power reaches Earth, is a type of energy that (as its name suggests) combines both electrical and magnetic energy. Another important form of energy in the Earth system is thermal, or heat, energy, which is the kinetic energy of molecules, since heat is simply the result of molecular motion.

Other types of energy include sound, chemical, and nuclear energy. Sound waves, which require a physical medium such as air in which to travel, are simply pressure fluctuations that carry varying levels of energy, depending on the frequency (pitch) and amplitude (volume) of the waves. Chemical energy makes possible the forming and releasing of molecular bonds, and, for this reason, chemical reactions often are accompanied by the production of heat. Whereas chemical energy concerns the bonds *between* atoms, nuclear energy relates to the bonds *within* them. Nuclear fission reactions involve the splitting of an atomic nucleus, while nuclear fusion is the joining of nuclei.

Heat and Thermodynamics

Thermodynamics is the study of the relationships between heat, work, and energy. As with

work, energy, and power, heat and the related concept of temperature are terms that have special definitions in the physical sciences. Heat itself is not to be confused with thermal energy, which, as noted earlier, is the kinetic energy that arises from the motion of particles at the atomic or molecular level. The greater the movement of these particles relative to one another, the greater the thermal energy.

Heat is internal thermal energy that flows from one body of matter to another. It is not the same as the energy contained in a system—that is, the internal thermal energy of the system. Rather than being "energy-in-residence," heat is "energy-in-transit." This may seem a little confusing, but all it means is that heat, in its scientific sense, exists only when internal energy is being transferred. As for temperature, it is not (as is commonly believed) a measure of heat and cold. Instead, temperature indicates the direction of internal energy flow between bodies and the average molecular kinetic energy in transit between those bodies.

In any case, temperature could not be a measure of heat and cold, as though these two were equal and opposing entities, because, scientifically speaking, there is no such thing as cold—only an absence of heat. When we place an ice cube in a cup of coffee, we say that the ice is there to "cool the coffee down," but, in fact, the opposite is happening: the coffee is warming up the ice cube, and in the process of doing so, it loses heat. This may seem like a difference of semantics, but it is not. It is a physical law that the flow of heat is always from a high-temperature reservoir to a low-temperature reservoir. Even air conditioners and refrigerators work by pulling heat out of a compartment rather than by bringing cold *in*.

MEASURING TEMPERATURE AND HEAT. Temperature, of course, can be measured by either the Fahrenheit or the Centigrade scales familiar in everyday life. Scientists, however, prefer the Kelvin (K) scale, established by William Thomson, Lord Kelvin (1824–1907). Drawing on the discovery made by the French physicist and chemist J. A. C. Charles (1746–1823) that gas at 0°C (32°F) regularly contracts by about 1/273 of its volume for every Celsius degree drop in temperature, Thomson derived the value of absolute zero (the temperature at which molecular motion virtually ceases) as –273.15°C (–459.67°F). The Kelvin and Celsius scales are thus directly related: Celsius temperatures can be converted to Kelvin units (for which neither the word nor the symbol for "degree" is used) by adding 273.15.

Heat, on the other hand, is measured not by degrees but by the same units as work. Energy is the ability to perform work, so heat or work units are also units of energy. Aside from the joule, heat often is measured by the kilocalorie, or the amount of heat that must be added to or removed from 1 kg of water to change its temperature by 1°C. As its name suggests, a kilocalorie is 1,000 calories, a calorie being the amount of heat required to change the temperature in 1 g of water by 1°C. The dietary calorie with which most people are familiar, however, is the same as a kilocalorie.

The Laws of Thermodynamics

The three laws of thermodynamics collectively show that it is impossible for a system to produce more energy than was put into it or even to produce an equal amount of usable energy. In other words, a perfectly efficient system—whether an engine or the entire Earth—is an impossibility. Derived during a period of about 60 years beginning in the 1840s, the laws of thermodynamics helped scientists and engineers improve the machines that powered the height of the Industrial Age. They also revealed the impossibility of constructing anything approaching a perpetual-motion machine, that great quest of dreamers over the ages, which the laws of thermodynamics proved to be an impossible dream.

THE FIRST LAW OF THERMODYNAMICS. The first law of thermodynamics is related to the conservation of energy, a physical law whereby the total energy in a system remains the same, though transformations of energy from one form to another take place. Such transformations occur frequently in the Earth system, as when a plant receives electromagnetic energy from the Sun and converts it to chemical potential energy in the form of carbohydrates. Likewise humans, by building dams, can harness the gravitational potential energy of flowing water and convert it into electromagnetic energy.

The conservation of energy, in effect, states that "the glass is half full," meaning that we can obtain as much energy from a system as we put into it. While saying the same thing, the first law of thermodynamics in effect states that "the glass

is half empty,": that is, that we can obtain *no more* energy from a system than we put into it. According to this law, because the amount of energy in a system remains constant, it is impossible to perform work that results in an energy output greater than the energy input.

The term *law* in the physical sciences is no empty expression; it means that a principle has been shown to be the case always and may be expected to remain the case in all situations. It is possible, of course, for a physical law to be overturned in light of later evidence. It is not likely, however, that any set of circumstances in the universe will ever disprove the core truth behind this law, which may be stated colloquially as "You can't get something for nothing."

THE SECOND LAW OF THERMODYNAMICS. In a 1959 lecture published as *The Two Cultures and the Scientific Revolution,* the British writer and scientist C. P. Snow (1905–1980) compared transfers of heat and energy to a game. The laws of thermodynamics are its rules, and, as Snow stated, the first law proves that it is impossible to win at this game, while the second law shows the impossibility of breaking even.

The second law of thermodynamics is more complicated than the first and is stated in a number of ways, though they are all interrelated. According to this law, spontaneous or unaided transfers of energy are irreversible and impossible without an increase of entropy in the universe. Entropy is the tendency of natural systems toward breakdown, specifically, the tendency for the energy in a system to be dissipated or degraded. (Later in this essay, we discuss examples of energy that has been degraded—for instance, wood that has been burned to produce ashes.) The second law means that spontaneous processes are irreversible and that it is impossible, without the additional input of energy, to transfer heat from a colder to a hotter body or to convert heat into an equal amount of work.

Whereas the first law showed engineers the impossibility of building a perpetual-motion machine, the second law proves that it is impossible to build even a perfectly efficient engine. Of all the energy we put into our automobiles in the form of gasoline (which is chemical potential energy in the form of hydrocarbons derived from the fossilized remains of dinosaurs in the earth), only about 30% of it goes into moving the car forward. The rest is dissipated in a number of ways, chiefly through heat and sound. Entropy, as it turns out, is inescapable and as inevitable as death. In fact, death itself is a result of entropy in the systems of all living things.

THE THIRD LAW OF THERMODYNAMICS. The third law of thermodynamics is not as well known as the other two and has little bearing on the discussion at hand, but it deserves at least brief mention. According to the third law, at the temperature of absolute zero entropy also approaches zero, which might sound like a way out of the restrictions imposed by the first two laws. All it really means is that absolute zero is impossible to reach—or, as Snow put it, the third law shows that "you can't escape the game."

In 1824 the French physicist and engineer Nicolas Léonard Sadi Carnot (1796–1832) had shown that an engine could achieve maximum efficiency if its lowest operating temperature were absolute zero. His work influenced that of Kelvin, who established the absolute-temperature scale mentioned earlier. Additionally, Carnot's discoveries informed the development of the third law. Whereas the second law is not derived from the first (though it is certainly consistent with it), the third law relies on the second: if it is impossible to build a perfectly efficient engine, as the second law states, it is likewise impossible to reach absolute zero.

This, of course, has not stopped scientists from attempting to achieve absolute zero, most properly defined as the temperature at which the motion of the average atom or molecule is zero. Helium atoms, in fact, never fully cease their motion, even at temperatures very close to 0K—and scientists have come very, very close. In 1993 physicists at the Helsinki University of Technology Low Temperature Laboratory in Finland used a nuclear demagnetization device to achieve a temperature of 2.8×10^{-10}K, or 0.00000000028K. This amounts to a difference of only 28 parts in 100 billion between that temperature and absolute zero.

Earth's Energy Input

Just as households have financial budgets, a system such as Earth (see Earth Systems) has an energy budget. The latter may be defined as the total amount of energy available to a system or, more specifically, the difference between the



The Pohutu geyser at the Rotorua Whakarewarewa Thermal Area in North Island, New Zealand. *(© A. N. T./Photo Researchers. Reproduced by permission.)*

energy flowing into the system and the energy lost by it. Having reviewed the laws of thermodynamics, one might suspect that a great deal of energy is dissipated in the operation of the Earth system, and, of course, that is absolutely correct.

Earth receives 174,000 TW of energy, or 174 quadrillion J per second. Human civilization, by contrast, uses only 10 TW, or about 0.00574% as much as Earth's total energy. Of that total, there are three principal sources, though one of these

sources—the Sun—dwarfs the other two in importance. The breakdown of Earth's energy input, along with the percentage of the total that each portion constitutes, is as follows:

- Solar radiation: 99.985%
- Geothermal energy: 0.013%
- Tidal energy: 0.002%

SOLAR RADIATION. The Sun radiates electromagnetic energy, which, as mentioned previously, is a form of energy that produces both electric and magnetic fields. Electromagnetic energy travels in waves, and since waves follow regular patterns, it is possible to know that those waves with shorter wavelengths have a higher frequency and thus higher energy levels.

The electromagnetic spectrum contains a variety of waves, each with progressively higher energy levels, including long-wave and short-wave radio; microwaves (used for TV transmissions); infrared, visible, and ultraviolet light; x rays; and ultra-high-energy gamma rays. Visible light is only a very small portion of this spectrum, and each color has its own narrow wavelength range.

Red has the least energy and purple or violet the most; hence, the names *infrared* for light with less energy than red, and *ultraviolet* for light with more energy than violet. The order of these wavelengths of light, along with the colors between, is remembered easily by the mnemonic device ROY G. BIV (standing for red, orange, yellow, green, blue, indigo, and violet). (Actually, there are only six major color ranges, and the name really should be *ROY G. BV.*)

Although it covers the entire electromagnetic spectrum, energy from the Sun is referred to by earth scientists as short-wavelength radiation. This is because the solar energy that enters the Earth system is shorter in wavelength (and thus higher in energy level) than the energy returned to space by Earth. (We discuss the degradation of energy in the Earth system later in this essay.) Without solar radiation, the life-giving processes of the hydrosphere, biosphere, and atmosphere would be impossible. An example is photosynthesis, the biological conversion of electromagnetic energy to chemical energy in plants. (See the later discussion of photosynthesis and the food web.)

GEOTHERMAL ENERGY. A much smaller, but still significant component of Earth's energy budget is geothermal energy, the planet's internal heat energy. Much of this heat comes from Earth's core, which has temperatures as high as 8,132°F (4,500°C) and from whence thermal energy circulates throughout the planet's interior. Also significant is the heat from radioactive elements, most notably uranium and thorium, near Earth's surface.

This thermal energy heats groundwater, and thus the principal visible sources of geothermal energy include geysers, hot springs, and fumaroles—fissures, created by volcanoes, from which hot gases pour. There are several types of geothermal energy reserves, among them dry and wet steam fields. The first of these reserves occurs when groundwater boils normally, whereas in the second type of reserve, groundwater is superheated, or prevented from boiling even though its temperature is above the boiling point. In both cases the waters have a much higher concentration of gases and minerals than ordinary groundwater. Another type of reserve can be found under the ocean floors, where natural gas mixes with very hot water.

Geothermal energy powers seismic activity as well as volcanic eruptions and mountain building, which together have played a significant role in shaping Earth as we know it today. Aside from its obvious impact on the planet's terrain, geothermal energy has had an indirect influence on the transfer of vital elements from beneath Earth's surface, a benefit of volcanic activity. (See the later discussion of the human use of geothermal energy in this essay.)

TIDAL ENERGY. Whereas the principal form of energy in Earth's budget comes from the Sun and the secondary source from Earth itself, the third type of energy input to the Earth system comes chiefly from the Moon. The Sun also affects tides, but because of its close proximity to Earth, the Moon has more influence over the movements of our planet's ocean waters.

Though the Moon is much smaller than Earth, it is larger, in proportion to the planet it orbits, than any satellite in the solar system (with the possible exception of Pluto's moon Charon). Given this fact, combined with its close proximity to Earth, it is understandable that the Moon would exert a powerful pull on its host planet. The gravitational pull of the Moon (and, to a lesser extent, that of the Sun) on Earth causes the oceans to bulge outward on the side of Earth closest to the Moon. At the same time, the oceans

on the opposite side of the planet bulge in response. (See Sun, Moon, and Earth for more about tides and the bulges that result from the Moon's gravitational pull.)

This gravitational pull creates a torque that acts as a brake on Earth's rotation, producing a relatively small amount of energy that is dissipated primarily within the waters of the ocean. Incidentally, the lunar-solar tidal torque, by increasing the amount of time it takes Earth to turn on its axis, is causing a gradual increase in the length of a day. Today, of course, there are 365.25 days in a year, but about 650 million years ago there were 400 days. In other words, Earth made 400 revolutions on its axis in the period of time it took it to revolve around the Sun. The change is a result of the fact that Earth's rotation is being slowed by 24 microseconds a year.

Energy Profit and Loss

Focusing now on solar radiation, since it is by far the greatest source of energy input to the Earth system, let us consider Earth's energy budget in terms of "profit and loss." In other words, how much useful energy output is denied to Earth owing to the laws of thermodynamics and other factors?

First of all, a good 30% of the Sun's energy input is reflected back into space unchanged, without entering Earth's atmosphere. This results from our planet's *albedo,* or reflective power. Albedo is the proportion of incoming radiation that is reflected by a body (e.g., a planet) or surface such as a cloud: the higher the proportion of incoming radiation that a planet deflects, the higher its albedo. The latter is influenced by such factors as solar angle, amount of cloud cover, particles in the atmosphere, and the character of the planetary surface.

Another 25% of solar radiation is absorbed by the atmosphere, while about 45% is absorbed at the planetary surface by living and nonliving materials. Thus, electromagnetic energy from the Sun enters the atmosphere, biosphere, and hydrosphere, where it is converted to other forms of energy, primarily thermal. Some of this thermal energy, for instance, causes the evaporation of water, which cycles through the atmosphere and then reenters the hydrosphere as precipitation. In other cases, absorbed radiation drives atmospheric and hydrologic distribution mechanisms, including winds, water currents, and waves. A very small, but extremely significant portion of incoming solar radiation goes into plant photosynthesis, discussed later.

ENERGY DEGRADATION. The energy that enters the Earth system—not only solar radiation but also geothermal and tidal energy—ultimately leaves the system. As shown by the second law of thermodynamics, however, the energy that departs the Earth system will be in a degraded form compared with the energy that entered it.

In a steam engine, water in the form of steam goes to work to power gears or levers. In the process, it cools, and the resulting cool water constitutes a degraded form of energy. Likewise, the ashes that remain after a fire or the fumes that are a by-product of an internal combustion engine's operation contain degraded forms of energy compared with that in the original wood or gasoline, respectively. In the same way, Earth receives short-wavelength energy from the Sun, but the energy it radiates to space is in a long-wavelength form.

All physical bodies with a temperature greater than absolute zero emit electromagnetic energy in accordance with their surface temperatures, and the hotter the body, the shorter the wavelength of the radiation. The sunlight that enters Earth's atmosphere is divided between the visible portion of the spectrum and the high-frequency side of the infrared portion. (Note that the Sun emits energy across the entire electromagnetic spectrum, but only a small part gets through Earth's atmospheric covering.) Earth, with an average surface temperature of 59°F (15°C), is much cooler than the Sun, with its average surface temperature of about 10,000°F (5,538°C). The radiation Earth sends back into space, then, is on the low-frequency, long-wavelength side of the infrared spectrum.

NO ENERGY LOSS. In accordance with the conservation of energy, no energy truly has been lost. In a relatively simple system, such as an automobile, chemical potential energy enters the vehicle in the form of gasoline and, after being processed by the engine, exits in a variety of forms. There is the kinetic energy that turns the wheels; the thermal energy of the engine and exhaust; electromagnetic energy from the battery for the headlights, dashboard lights, radio, air conditioning, and so on; and the sound energy dissipated in the noise of the car. If one

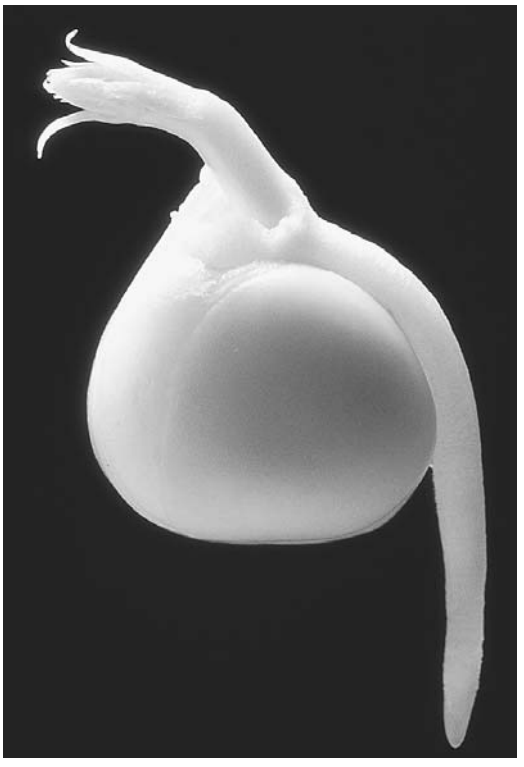
could add all those energy components together, one would find that all the energy that entered the system left the system. Note, however, that once again the process is irreversible: one can use gasoline to power a battery and hence a car radio, but the radio or the battery cannot generate gasoline.

The Earth system is much more complex, of course, but the same principle applies: about 174,000 TW of energy enter the system, and about 174,000 TW are used in the form of heat. Of the portion that enters the atmosphere, some goes into warming the planet, some into moving the air and water, and a very small part into the all-important biological processes described later, but *all* of it is used. It should be noted that Earth has a very small energy surplus, owing to the accumulation of undecomposed biomass that ultimately becomes fossil fuels; however, the amount of energy involved is minor compared with the larger energy budget. (For more information about biomass and fossil fuels, see the following discussion.)

THE GREENHOUSE EFFECT. Not only is there no net loss of energy in the universe, but Earth itself also possesses a remarkably efficient system for making use of the energy it receives. This is the greenhouse effect, whereby the planet essentially recycles the degraded energy it is in the process or returning to space.

Water vapor and carbon dioxide, as well as methane, nitrous oxide, and ozone, all absorb long-wavelength radiated energy as the latter makes its way up through the atmosphere. When heated, these radiatively active gases (as they are called) re-radiate the energy, now at even longer wavelengths. In so doing, they slow the planet's rate of cooling. Without the greenhouse effect, surface temperatures would be about 50°F (10°C) cooler than they are—that is, around 17.6°F (–8°C). This, of course, is well below the freezing temperature of water and much too cold for Earth's biological processes. Thus, the greenhouse effect literally preserves life on the planet.

It may be surprising to learn that the greenhouse effect, a term often heard in the context of dire environmental warnings, is a natural and healthful part of the Earth system. Like many useful things, the greenhouse effect is not necessarily better in larger doses, however, and that is the problem. It is believed that human activities have resulted in an increase of radiatively active gases, which could lead to global warming. Among such gases are the chlorofluorocarbons (CFCs) used in aerosol cans, now banned by international treaty. Also of concern are the high levels of carbon dioxide produced by the burning of fossil fuels.



A GERMINATING GARDEN PEA SEEKS SUNLIGHT FOR PHOTOSYNTHESIS. *(© J. Burgess/Photo Researchers. Reproduced by permission.)*

REAL-LIFE APPLICATIONS

Energy and the Living World

One of the most interesting components of the entire energy picture is the relationship of energy input, energy output, and the biosphere. Particularly important is the use of solar radiation for the purposes of photosynthesis, an activity that constitutes a small but vital sector of Earth's energy budget.

Though it accounts for only about 1% of the energy received from solar radiation, photosynthesis is essential to the sustenance of life. In photosynthesis, plants receive solar radiation, carbon dioxide, and water, which chemically react to produce carbohydrates and oxygen. Animals

depend not only on the oxygen but also on carbohydrates, such as sugars, and thus photosynthesis makes possible the development of the food chains that constitute the world of living creatures.

Food webs. Even though *food chain* is a well-known expression, modern scientists prefer the term *food web,* because it more accurately portrays the complicated relationships involved. The term food chain, as it is commonly used, implies a strict hierarchical structure in which (to use another popular phrase) "the big fish eat the little fish." In fact, the relationship between participants is not quite so neatly defined.

It is, however, possible to describe a food web in terms of a few key players, or types of players. There are primary producers, which are green plants, and primary consumers—herbivores, or plant-eating animals. Secondary consumers (and those at further levels, such as tertiary and quaternary) are either carnivores—that is, meat-eating animals who eat the herbivores—or omnivores, which are both plant and animal eaters. For example, omnivorous humans eat herbivorous cows, who have eaten plants.

Carnivores and omnivores, however, are not really at the top of the food chain, so to speak; rather, in line with the non-hierarchical idea of the food web, they represent points in an interlocking set of relationships. Materials from plants, herbivores, carnivores, and omnivores ultimately will all be consumed by the lowliest of creatures, that is, detritivores, or decomposers, including bacteria and worms. At each stage energy is transferred, and, as always, the second law of thermodynamics comes into play. The energy is degraded in transfer; specifically, the further away an organism is from the original plant source, the less a given quantity of fuel contributes to its growth. It is interesting to note the economy of energy use at the detritivore stage.

Worms and other decomposers are exceedingly efficient feeders, working the same food particles over and over and extracting more stored energy each time. They then produce waste products that increase the vitamin content of the soil, thus enabling the growth of plants and the continuation of the biological cycle. Also, detritivores may contribute directly (and, from the larger energy-cycle perspective, less efficiently) to providing fuel for carnivores, as when a bird eats a worm.

Bioenergy

The food web is the mechanism whereby energy is cycled through the biosphere, as fuel in the form of food. Plant matter and other biological forms also can serve as direct sources of heat, providing fuel that can be either burned without processing or converted into gas or alcohol. In such situations the plant matter is described as bioenergy, or energy derived from biological sources that are used as fuel.

Materials that are burned or processed to produce bioenergy are called biomass. Examples of the latter include wood logs burned on a fire, probably the oldest type of fuel known to humankind and still one of the principal forms of heating available in many developing countries. In fact, some of the least technologically advanced and most technologically advanced nations are alike in their use of another variety of biomass: waste.

Dried animal dung provides heating material in many a third world village where electricity is unknown, while at the other end of the technological spectrum, some Western municipalities extract burnable biomass from processed sewage. Since Western countries have at their disposal plenty of other energy sources, they typically burn off the methane gas and dried waste material from treated sewage simply as a means of removing it, rather than as an energy source. Those materials could provide usable energy, however.

The products of sewage treatment, of course, are the result of processing, which involves the conversion of biomass to either gases (for example, methane, as mentioned previously) or alcohol. Farmers in rural China, for instance, often place agricultural waste and sewage in small closed pits, from whence they extract burnable methane gas. In the United States, Brazil, and other countries with abundant farmland, some of the agricultural output is directed not toward production of food but toward production of fuel in the form of ethanol, a type of alcohol made from sugarcane, corn, or sorghum grain. Ethanol can be mixed with gasoline to run an automobile or burned alone in specially modified engines. In either case, the fuel burns much

more cleanly, producing less poisonous carbon monoxide than ordinary gasoline.

Fossil Fuels

Biomass is potentially renewable, whereas another source of bioenergy is not. This is the bioenergy from fossil fuels—buried deposits of petroleum, coal, peat, natural gas, and other organic compounds. (Actually, fossil fuels typically are considered separate from other forms of bioenergy, because they are nonrenewable.)

Fossil fuels are the product of plants and animals that lived millions of years ago, died, decomposed, and became part of Earth's interior. Over the ages, as more sediment weighed down on these organic deposits, the weight applied more pressure, generated more heat, and led to the concentration of this decomposed material, which became a valuable source of energy.

USING UP RESOURCES. Given the vast spans of time that have passed, as well as the almost inconceivable numbers of plants and animals, the supplies of fossil-fuel energy stored under Earth's surface are enormous. But they are *not* infinite, and, as noted earlier, they are nonrenewable; once they are gone, they might as well be gone forever, because it would take hundreds of millions of years to produce additional deposits. Furthermore, humans are using up these energy sources at an alarming rate.

Up until about 1750, Earth's fossil-fuel deposits were largely intact, but after that time industrialized societies began to extract coal for heating, transportation, and industrial uses. Today it remains a leading means of generating electrical power. During the twentieth century, petroleum increasingly was directed toward transportation, and this led to the extraction of still more of Earth's fossil-fuel deposits. If civilization continues to consume these products at its current rate, reserves will be exhausted long before the end of the twenty-first century.

SEARCHING FOR ENERGY SOURCES. There are several reasons not to panic over the loss of fossil-fuel resources. First, known reserves are just that—they are the ones that energy companies, and their geologists, know about at the present time. As long as plentiful resources are available, corporations and governments do not feel a pressing need to search for more, but as those resources are used up, such searches become economically necessary. For a time at least, these searches will continue to yield new (though increasingly harder to reach) deposits.

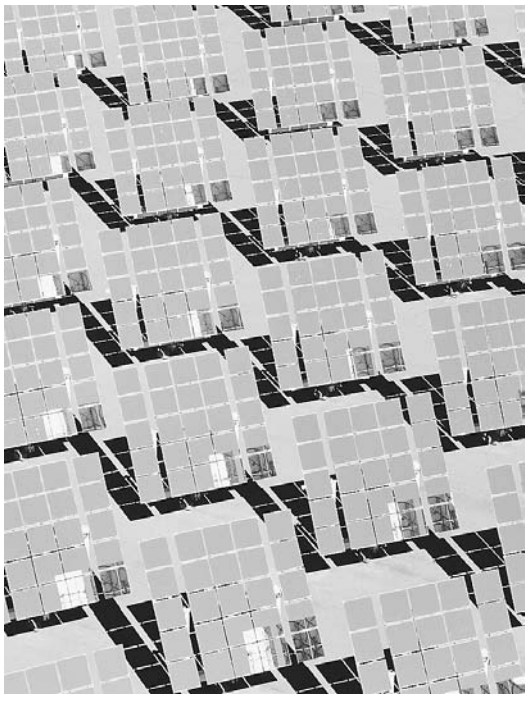
Also, fears about Earth running out of fuel are built on the assumption that no one will develop other sources of energy, a few of which are discussed at the conclusion of this essay. Though most of the known alternative energy sources face their own challenges, it is thoroughly conceivable that scientists of the future will develop means of completely replacing fossil fuels as the source of electrical power, fuel for transport, and other uses. After all, there was once a time (during the second half of the nineteenth century) when Americans became increasingly anxious over dwindling reserves of a vital energy resource essential for powering the nation's lamps: whale oil.

Environmental Concerns

While the loss of energy reserves may not be an immediate cause for panic, the effects of fossil-fuel burning on the environment have alarmed scientists and environmentalists alike. At the most basic level, there is the environmental impact posed by the extraction of fossil fuels. Coal mines, for instance, have been used up and now sit abandoned, their land worthless for any purpose. There is also the environmental danger created by hazards in misuse or transport of fossil fuels—for example, the vast oil spill caused by the grounding of the Exxon *Valdez* near Alaska's Prince William Sound in 1989.

By far the greatest environmental concern raised by fossil fuels, however, is the effect they produce in the atmosphere when burned. For instance, one of the impurities in coal is sulfur, and when coal burns, the sulfur reacts with oxygen in the combustion process to create sulfur dioxide and sulfur trioxide. Sulfur trioxide reacts with water in the air, creating sulfuric acid and thus acid rain, which can endanger plant and animal life as well as corrode metals and building materials.

THE GREENHOUSE EFFECT REVISITED. Even greater fears center on the release into the atmosphere of carbon monoxide and carbon dioxide, both of which are by-products in the burning of fossil fuels. The first is a poison, whereas the second is a vital part of the life cycle, yet carbon dioxide, in fact, may pose the greater threat.



An array of solar reflectors near Albuquerque, New Mexico, harnesses solar power. *(© J. Mead/Photo Researchers. Reproduced by permission.)*

Earlier we discussed the greenhouse effect, which, when it occurs naturally, is important to the preservation of life on the planet. The large number of internal-combustion engines in operation on Earth today produce an inordinate amount of carbon dioxide, which in turn provides the atmosphere with more radiatively active gas than it needs. According to many environmentalists, the result is, or will be, global warming. If it takes place over a long period of time, global warming could bring about serious hazards—in particular, the melting of the polar ice caps. It should be noted, however, that not all scientists are in agreement that global warming is occurring or that humans are the principal culprits inducing these environmental changes.

Alternative Energy Sources

Whatever the merits of the various sides in the debate on global warming or the exhaustion of fuel resources, one need hardly be an environmentalist to agree that the world cannot forever rely only on existing fossil fuels and the technology that uses them. Today, even as scientists in laboratories around the world work to develop viable alternative means of powering industry, utilities, and transportation, many alternative energy sources are already in use.

Some of these energy forms are very old, for instance, burnable biomass, water power, or wind power, all of which date back to ancient times. Others are extremely new in concept, most notably, nuclear energy, which was developed in the twentieth century. Still others are new, high-tech versions of old-fashioned energy sources, the best example being solar power. In fact, all three major contributors to Earth's energy budget—solar radiation, tidal energy, and geothermal energy (discussed further later in this essay)—have been harnessed by human societies.

HIGH-TECH ENERGY SOLUTIONS. Several of the more ambitious ideas for energy creation, while they may capture people's imaginations, have significant drawbacks. There is the proposal, for instance, to extract hydrogen gas from water by means of electrolysis, potentially providing an extremely clean, virtually limitless source of energy. Hydrogen gas, however, is highly flammable, as the 1937 explosion of the airship *Hindenburg* illustrated, and, in any case, the fuel to provide the electricity necessary for electrolysis would have to come from somewhere, presumably, the burning of fossil fuels.

Nuclear energy, of course, has frightened many people in the wake of such well-known disasters as those that occurred at Three Mile Island, Pennsylvania, in 1979 and Chernobyl, in the former Soviet Union, in 1986. In fact, those two situations illustrate more about governments than they do about technology itself. No one died at Three Mile Island, and with an open society and media access to the site, the public outcry became so great that the plant was closed. By contrast, the Soviets' outmoded technology helped bring about the Chernobyl disaster, and the communist dictatorship's practice of censorship and suppression led to a massive cover-up that greatly increased the death toll. As a result, thousands died at Chernobyl, and thousands more died as the result of the indirect effects of nuclear pollution in the environment.

There is no question, however, that nuclear energy does pose an enormous potential environmental threat from its waste products. Spent fuel rods, if simply buried, eventually leak radioactive waste into the water table and could kill or harm vast populations. This all relates to nuclear *fission,* the only type of peaceful nuclear

KEY TERMS

ABSOLUTE ZERO: The temperature at which all molecular motion virtually ceases.

ALBEDO: The reflective power of a surface or body or, more specifically, the proportion of incoming radiation that the surface or body reflects.

ATMOSPHERE: In general, an atmosphere is a blanket of gases surrounding a planet. Unless otherwise identified, however, the term refers to the atmosphere of Earth, which consists of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon, which together comprise 0.07%.

BIOENERGY: Energy derived from biological sources that are used directly as fuel (as opposed to food, which becomes fuel).

BIOMASS: Materials that are burned or processed to produce bioenergy.

BIOSPHERE: A combination of all living things on Earth—plants, mammals, birds, reptiles, amphibians, aquatic life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

CALORIE: A measure of heat or energy in the SI, or metric, system, equal to the heat that must be added to or removed from 1 g of water to change its temperature by 1°C. The dietary calorie with which most people are familiar is the same as the kilocalorie, or 1,000 calories.

CONSERVATION OF ENERGY: A law of physics that holds that within a system isolated from all outside factors, the total amount of energy remains the same, though transformations of energy from one form to another take place. The first law of thermodynamics is the same as the conservation of energy.

ELECTROMAGNETIC ENERGY: A form of energy with electric and magnetic components, which travels in waves.

ELECTROMAGNETIC SPECTRUM: The complete range of electromagnetic waves on a continuous distribution from a very low range of frequencies and energy levels, with a correspondingly long wavelength, to a very high range of frequencies and energy levels, with a correspondingly short wavelength. Included on the electromagnetic spectrum are long-wave and short-wave radio; microwaves; infrared, visible, and ultraviolet light; x rays; and gamma rays.

ENERGY: The ability of an object (or in some cases a nonobject, such as a magnetic force field) to accomplish work.

ENERGY BUDGET: The total amount of energy available to a system or, more specifically, the difference between the energy flowing into the system and the energy lost by it.

ENTROPY: The tendency of natural systems toward breakdown and, specifically, the tendency for the energy in a system to be dissipated. Entropy is related closely to the second law of thermodynamics.

ENVIRONMENT: In discussing systems, the term environment refers to the surroundings—everything external to and separate from the system.

KEY TERMS CONTINUED

FIRST LAW OF THERMODYNAMICS: A law of physics stating that the amount of energy in a system remains constant, and therefore it is impossible to perform work that results in an energy output greater than the energy input. This is the same as the conservation of energy.

FOSSIL FUELS: Nonrenewable forms of bioenergy, including petroleum, coal, peat, natural gas, and other organic compounds usable as fuel.

FREQUENCY: The number of waves, measured in Hertz, passing through a given point during the interval of one second. The higher the frequency, the shorter the wavelength.

GEOTHERMAL ENERGY: Heat, or thermal, energy from Earth's interior.

GREENHOUSE EFFECT: Warming of the lower atmosphere and surface of Earth. This occurs because of the absorption of long-wavelength radiation from the planet's surface by certain radiatively active gases, such as carbon dioxide and water vapor, in the atmosphere. These gases are heated and ultimately re-radiate energy at an even longer wavelength to space.

HEAT: Internal thermal energy that flows from one body of matter to another.

HERTZ: A unit for measuring frequency, equal to one cycle per second. High frequencies are expressed in terms of kilohertz (kHz; 10^3 or 1,000 cycles per second), megahertz (MHz; 10^6 or one million cycles per second), and gigahertz (GHz; 10^9 or one billion cycles per second.)

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

JOULE: The SI measure of work. One joule (J) is equal to the work required to accelerate 1 kg of mass by 1 m per second squared (1 m/s^2) over a distance of 1 m. Owing to the small size of the joule, however, it often is replaced by the kilowatt-hour, equal to 3.6 million (3.6×10^6) J.

KELVIN SCALE: Established by William Thompson, Lord Kelvin (1824–1907), the Kelvin scale measures temperature in relation to absolute zero, or 0K. (Note that units in the Kelvin system, known as kelvins, do not include the word or symbol for "degree.") The Kelvin scale, which is the system usually favored by scientists, is related directly to the Celsius scale; hence, Celsius temperatures can be converted to kelvins by adding 273.15.

KINETIC ENERGY: The energy that an object possesses by virtue of its motion.

LAW: A scientific principle that is shown always to be the case and for which no exceptions are deemed possible.

MASS ENERGY: The energy an object possesses by virtue of its mass. Sometimes called *rest energy.*

NUCLEAR FISSION: A nuclear reaction that involves the splitting of an atomic nucleus.

NUCLEAR FUSION: A nuclear reaction that involves the joining of atomic nuclei.

NUCLEUS: The center of an atom, a region where protons and neutrons are located and around which electrons spin.

KEY TERMS CONTINUED

PHOTOSYNTHESIS: The biological conversion of light energy (that is, electromagnetic energy) to chemical energy in plants.

POTENTIAL ENERGY: The energy that an object possesses by virtue of its position or its ability to perform work.

POWER: The rate at which work is accomplished over time, a figure rendered mathematically as work divided by time. The SI unit of power is the watt, while the British unit is the foot-pound per second.

RADIATION: The transfer of energy by means of electromagnetic waves, which require no physical medium (for example, water or air) for the transfer. Earth receives the Sun's energy via the electromagnetic spectrum by means of radiation.

RADIOACTIVITY: A term describing a phenomenon whereby certain materials are subject to a form of decay brought about by the emission of high-energy particles or radiation. Forms of particles or energy include alpha particles (positively charged helium nuclei), beta particles (either electrons or subatomic particles called positrons), or gamma rays, which occupy the highest energy level in the electromagnetic spectrum.

SECOND LAW OF THERMODYNAMICS: A law of physics stating that spontaneous or unaided transfers of energy are irreversible and impossible without an increase of entropy in the universe. It is therefore impossible, without the additional input of energy, to transfer heat from a colder to a hotter body or to convert heat into an equal amount of work.

SI: An abbreviation of the French term *Système International d'Unités,* or International System of Units. Based on the metric system, SI is the system of measurement units in use by scientists worldwide.

SYSTEM: Any set of interactions that can be set apart mentally from the rest of the universe for the purposes of study, observation, and measurement.

TEMPERATURE: The direction of internal energy flow between two systems when heat is being transferred. Temperature measures the average molecular kinetic energy in transit between those systems.

TERAWATT: See *watt.*

THERMAL ENERGY: Heat energy, a form of kinetic energy produced by the motion of atomic or molecular particles in relation to one another. The greater the relative motion of these particles, the greater the thermal energy.

WATT: The metric unit of power, equal to 1 J per second. Because this is such a small unit, scientists and engineers typically speak in terms of kilowatts, or units of 1,000 W. Very large figures, such as those relating to Earth's energy budget, usually are given in terawatts, or 10^{12} (one trillion) W.

WAVELENGTH: The distance between a crest and the adjacent crest or the trough and an adjacent trough of a wave. Wavelength is related inversely to frequency, meaning that the shorter the wavelength, the higher the frequency.

WORK: The exertion of force over a given distance. In the metric, or SI, system, work is measured by the joule (J) and in the British system by the foot-pound (ft-lb).

power in use today. In building the hydrogen bomb in the mid-twentieth century, physicists and chemists used the much greater power of nuclear *fusion,* or the bonding of atomic nuclei. If nuclear fusion could be produced in controlled reactions, for peaceful use, it would provide safe, cheap, limitless power to the planet.

GEOTHERMAL ENERGY. Unless or until nuclear fusion or some more advanced alternative energy source is developed, societies will continue to rely on fossil fuels for the bulk of their energy needs. At the same time, alternative sources will continue to supply energy in certain situations. An excellent example of such a source is geothermal energy, harnessed by peoples in areas as widespread as New Zealand and Iceland centuries ago.

Long before the first Europeans arrived in New Zealand, the native Maori people used geothermal energy from geysers to cook food. Modern applications of geothermal energy began with the creation of the first geothermal well, by workers who accidentally drilled into one in Hungary in 1867. Today Hungary is the world's leading producer and consumer of geothermal energy, followed closely by Italy and Iceland. The word *fumarole,* used earlier in this essay, is Italian in origin, and it is said that the fumaroles near the town of Lardarello, used for the production of electricity since 1904, once inspired Dante Alighieri's (1265–1321) vision of the Inferno, as captured in his celebrated work by that name. As for Iceland, more than 99% of the buildings in the capital city of Reykjavik use geothermal energy for heat.

Heat is not the primary human application for geothermal energy. As noted earlier, in the context of the first law of thermodynamics, energy can be converted from one form to another. Thus, geothermal energy is applied for the creation of electromagnetic energy: steam or heated water from the ground runs turbines, which produce electricity.

Geothermal energy has enormous advantages, including the fact that its raw materials (heated water and steam) are free and relatively inexpensive to extract. It is also inexpensive environmentally, causing virtually no air pollution. Will geothermal energy ever significantly compete with fossil fuels as a significant source of energy for humans? It is conceivable, but at present a number of barriers exist. Geothermal resources exist only in very specific parts of the world, and the extraction of the raw materials may release noxious gases, such as hydrogen sulfide (the same compound that gives intestinal gas its smell). Also, ironically, there are environmental concerns, not because of true damage but because geothermal mines often pose a threat of sight pollution in the midst of otherwise gorgeous natural settings.

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EARTH'S INTERIOR

EARTH'S INTERIOR
PLATE TECTONICS
SEISMOLOGY

EARTH'S INTERIOR

CONCEPT

For the most part, this book is concerned with geologic, geophysical, and geochemical processes that take place on or near Earth's surface. Even the essay Plate Tectonics, which takes up one of the central ideas in modern earth sciences, discusses only the lithosphere and crust but not the depths of the mantle or the core. Yet there are several good reasons to study Earth's interior, even if it is not immediately apparent why this should be the case. At first glance it would seem that activities in Earth's interior could hardly be removed further from day-to-day experience. By contrast, even the Moon seems more related to daily life. At least it is something we can see and a place to which humans have traveled; on the other hand, no human has ever seen the interior of our planet, nor is anyone likely to do so. What could Earth's interior possibly have to do with everyday life? The answer may be a bit surprising. As it turns out, many factors that sustain life itself are the result of phenomena that take place far below our feet.

HOW IT WORKS

The Core: Gravity and Density

In the essay on Planetary Science, there is a discussion of an age-old question: "Why is the earth round?" or rather "Why is Earth a sphere?" The answer, explained in more detail within the context of that essay, is that gravitational force dictates a spherical shape. As far as we know, there is no such thing as a planet or sun in the shape of a cube, because for every large object, the gravitational pull from the interior forces it to assume a more or less uniform shape. Since there is no shape more perfectly uniform than that of a sphere, this is the typical form of bodies that possess large mass.

In fact, the greater the mass, the greater the tendency toward roundness. Although they are less dense than Earth, Jupiter and Saturn are certainly more massive, and therefore they are more perfectly round. Mars and the Moon, on the other hand, are less so. Earth is not perfectly round, owing to the fact that its mass bulges at the equator because it is moving; if it were still, it would be quite round indeed, a result of the great mass at its core.

A MASSIVE CORE. As we shall see, nearly a third of Earth's mass is at its core, even though the core accounts for only about a fifth of its total volume. In other words, Earth's core is exceptionally dense, and this has several implications. First of all, the planet has a powerful gravitational pull, which not only serves to keep people and other objects rooted on the surface of the solid earth but also holds our atmosphere in place.

The gravitational attraction between any two objects is related directly to mass and inversely to the distance between them. Everything in the universe exerts some degree of gravitational pull on everything else, but unless at least one of the objects is of significant mass, the total gravitational force is negligible. The reason for this—as determined by the English mathematician and physicist Sir Isaac Newton (1642–1727)—is that gravitational force between two objects is the product of their mass divided by the distance between them and multiplied by



SIR ISAAC NEWTON *(Library of Congress.)*

an extremely small quantity known as the *gravitational constant.*

In the case of Earth, there is an extremely large amount of mass at the interior. Moreover, that mass is at a relatively short distance from objects on the planet's surface—or, to put it another way, Earth has a relatively small radius. Hence its powerful gravitational pull—one of many ways that the interior of Earth affects the overall conditions of the planet.

DENSITY OF TERRESTRIAL AND JOVIAN PLANETS. Saying that a large amount of mass is concentrated in a small area on Earth is another way of saying that the planet's interior is extremely dense. As it turns out, Earth is, in fact, the densest planet in the solar system; indeed the only other planets that come close are Mercury and Venus.

Mercury, Venus, Earth, and Mars together are designated as the terrestrial planets: bodies that are small, rocky, and dense; have relatively small amounts of gaseous elements; and are composed primarily of metals and silicates. (See the essay Minerals for more on metals as well as the extremely abundant silicates.) By contrast, the Jovian planets—Jupiter, Saturn, Uranus, and Neptune—are large, low in density, and composed primarily of gases. (Scientists know little about Pluto, which was discovered in the early twentieth century. It has a density higher than any Jovian planet, but there is little basis for classifying it as a terrestrial planet.)

Saturn, which is the least dense among the planets, has a mass only about 100 times as great as that of Earth, while its volume is almost 800 times greater. Thus its density is only about 12% of Earth's. And whereas Jovian planets, such as Saturn, are mostly gaseous and solid only in their small, dense cores, Earth is extremely solid. For a Jovian planet, there is little distinction between the "atmosphere" and the surface of the planet itself, whereas anyone who has ever jumped from a great height on Earth can attest to the sharp difference between thin air and solid ground.

Beneath that solid ground is a planetary interior composed of iron, nickel, and traces of other elements. The vast mass of the interior not only gives Earth a strong gravitational pull but also, in combination with the comparatively high speed of the planet's rotation, causes Earth to have a powerful magnetic field. Furthermore, Earth is distinguished even from most terrestrial planets (among which the Moon sometimes is counted) owing to the high degree of tectonic activity beneath its surface.

PLATE TECTONICS AND THE INTERIOR

Of all the terrestrial planets, Earth is the only one on which the processes of plate tectonics take place. Tectonism is the deformation of the lithosphere, the brittle area of Earth's interior that includes the crust and upper mantle. (We take a closer look at these regions later in this essay.) The lithosphere is characterized by large, movable segments called plates, and plate tectonics is the name both of a theory and of a specialization of tectonics, or the study of tectonism.

As a realm of study, plate tectonics deals with the large features of the lithosphere and the forces that shape them. As a theory, it explains the processes that have shaped Earth in terms of plates and their movement. This theory, discussed in detail within the Plate Tectonics essay, brings together aspects of seismic (earthquake) and volcanic activity, the structures of Earth's crust, and other phenomena to provide a unifying model of Earth's evolution. It is one of the dominant concepts in the modern earth sciences.



THE FOUR PLANETS OF THE INNER SOLAR SYSTEM, WITH THE SUN. MERCURY, VENUS, EARTH, AND MARS ARE DESIGNATED THE TERRESTRIAL PLANETS—SMALL, ROCKY, DENSE, AND COMPOSED OF METALS AND SILICATES WITH FEW GASEOUS ELEMENTS. *(© Photo Researchers. Reproduced by permission.)*

THE IMPORTANCE OF TECTONIC ACTIVITY. As discussed in Plate Tectonics, there is a difference in thickness between continental and oceanic plates on Earth. By contrast, the other terrestrial planets have crusts of fairly uniform thickness, suggesting that they have experienced little in the way of tectonic activity. Several other factors indicate that Earth is by far the most prone to tectonic activity.

Earth's core is enormous, larger than the entire planet Mercury. This means that there is a large area of high pressure and high heat driving tectonic processes, as we discuss later in this essay. In addition, Earth has a relatively thin lithosphere, meaning that the effects of heat below the lithosphere are manifested dramatically above it in the form of shifting plates and the results of such shifts—for instance, mountain building.

REAL-LIFE APPLICATIONS

"DIGGING TO CHINA"

As children, many people growing up in the West heard something along these lines: "If you could dig a hole straight through the earth, you would end up in China." This might be more or less literally true, since eastern China is on the opposite

side of the planet from eastern North America. (Southeast Asia, however, is farther away, because it is more exactly opposite the eastern seaboard.) Even with the most sophisticated equipment imaginable, however, it is unlikely that anyone will put a hole straight through Earth.

The idea of "digging to China" may have raised a new question in many a child's mind. Suppose a person were to dig a hole through the Earth and jump down into it. What would happen? Gravity would carry the person to the center of the earth, but after that, would he or she just go on flying past the gravitational center of the planet? It is a good question, and the likelihood is that the powerful gravitational force at the center of the earth would hold the person there. Again, however, the likelihood of ever conducting such an experiment—for instance, with a steel ball that emitted a radio signal—is slim.

How deep? The reason for this slim likelihood can be illustrated by visiting some of the world's deepest mines. There is, for instance, the Homestake Gold Mine in South Dakota, one of the deepest mines in the United States, which extends to about 8,500 ft. (2,591 m) below the surface. This is about 1.6 mi. (2.6 km), almost six times as deep as the height of the world's tallest building, the Petronas Towers in Malaysia.

Impressive as the Homestake is, it is almost insignificant when compared with the Western Deeps Gold Mine, near Carletonville, South Africa, which reaches down about 13,000 ft. (3,962 m)! In a mine such as the Western Deeps, or even the Homestake, temperatures can reach 140°F (60°C), which makes working in such an environment extremely hazardous. Mines are air-conditioned to make them bearable, but even so, there are other dangers associated with the great depth. For instance, the pressure caused by the rocks lying above the mine may become so great that rocks in the wall shatter spontaneously.

It is no wonder, then, that workers in extremely deep gold mines and diamond mines are well paid or that their insurance premiums are very expensive. Yet even the Western Deeps is not the deepest spot where humans have drilled holes on Earth. Scientists in Sweden and Russia have overseen the drilling of deep holes purely for research purposes, while in Louisiana and Oklahoma, a few such holes have been drilled in the process of exploring for petroleum. The deepest of these holes are at Andarko Basin, Oklahoma, and the Kola Peninsula, Russia, where artificial holes extend to a staggering 7.5 mi. (12 km). This is more than three times as far down as the Western Deeps, and it is hard to imagine how any human could survive at such depths.

How do we know? Even these deepest excavations represent only 0.2% of the distance from Earth's surface to its core, which is about 3,950 mi. (6,370 km) below our feet. Given that fact, one might wonder exactly how it is that earth scientists—particularly geophysicists—claim to know so much about what lies beneath the crust. In fact, they have a number of fascinating tools and methods at their disposal.

Among these tools are such rocks as kimberlite and ophiolite, which originate deep in the crust and mantle but move upward to the surface. In addition, meteorites that have landed on Earth are believed to be similar to the rocks at the mantle and core, since the planet was originally a cloud of gas around which solid materials began to form as a result of bombardment from outer space (see the essays Sun, Moon, and Earth and Planetary Science). Most important of all are seismic, or earthquake, waves, whose speed, motion, and direction tell us a great deal about the materials through which they have passed and the distances over which they have traveled.

An Imaginary Journey

Having established just how far humans would have to go to penetrate even just below Earth's crust with existing technology, let us now pretend that such obstacles have been overcome. In this imaginary situation, through a miracle of science let us say that there really is a hole straight through the earth and an elevator that passes through it.

This, of course, raises still more complications, aside from the gravitational problem mentioned earlier. Among other things, our elevator would have to be made of a heat-resistant material, given the temperatures we are likely to encounter in our descent. It may have sounded hot in the gold mines of South Africa and South Dakota, but that will seem cool by the time we reach Earth's core, which is as hot as the Sun's surface.

Starting out. For now, however, we will throw all those logistical problems out the window and begin our journey to the center of the earth. In so doing, we will pass through three

major regions—crust, mantle, and core—as well as several subsidiary realms within. By far the smallest of these is the crust, which is also the only part about which we know anything from direct experience.

Very quickly we find ourselves passing through the A, B, and C horizons of soil discussed in the Soil essay, and soon we are passing through bedrock into the main part of the crust. Bedrock might be only 5-10 ft. deep (1.5–3 m), or it might be half a mile deep (0.8 km) or perhaps even deeper. Although this is a long way for a person to dig, we still have barely scratched the surface.

As noted earlier, there is a difference between continental crust and oceanic crust. We will ignore the details here, except to say that the continental crust is thicker but the oceanic crust is denser. Thus, the continents are at a higher elevation than the oceans around them. Depending on whether the crust is oceanic or continental, we have between 3 mi. and 40 mi. (5–70 km) to travel before we begin to pass out of the crust and into the mantle.

THE LITHOSPHERE, SEISMOLOGY, AND REMOTE SENSING. The transition from crust to mantle is an abrupt one, marked by the boundary zone known as the Mohorovicic discontinuity. Sometimes called the M-discontinuity or, more commonly, the Moho, it was the discovery of the Croatian geologist Andrija Mohorovicic (1857–1936). On October 8, 1909, while studying seismic waves from an earthquake in southeastern Europe, Mohorovicic noticed that the speed of the waves increased dramatically at a depth of about 30 mi. (50 km).

Since waves travel faster through denser materials, Mohorovicic reasoned that there must be an abrupt transition from the rocky material in the Earth's crust to denser rocks below. His discovery is an excellent example of remote sensing (see Remote Sensing), whereby earth scientists are able to study places and phenomena that are impossible to observe directly.

After the Moho, which is only about 0.1-1.9 mi. (0.2–3 km) thick, we enter the mantle—or, more specifically, the lithospheric mantle. This subregion may extend to depths between 30 mi. and 60 mi. (50–100 km) and is much more dense than the crust. Like the crust, it is brittle, solid, and relatively cool compared with the regions below; hence, the crust and lithospheric mantle are lumped together as the lithosphere.

The Asthenosphere and Its Impact

At the base of the lithosphere, we pass through another transition zone, known as the Gutenberg low-velocity zone (named after the German-born American seismologist Beno Gutenberg [1889–1960]), where the speed of seismic waves again increases dramatically. After that, we enter a layer of much softer material, known as the asthenosphere. The material in the asthenosphere is soft not because it is weak—on the contrary, it is made of rock—but because it is under extraordinarily high pressure.

What happens in the asthenosphere plays a powerful role in life on the surface. The plates of the lithosphere float, as it were, atop the molten rock of the asthenosphere, which forces these plates against one another as though they were ice cubes floating in a bowl of water in constant motion. This motion is the phenomenon of plate tectonics, which, as we have discussed, quite literally shapes the world we know.

VOLCANISM AND THE ATMOSPHERE. Plate tectonics is responsible not only for such phenomena as the creation of mountains but also, by influencing the development of volcanoes, indirectly for Earth's atmosphere. In the first few billion years of the planet's existence, the action of volcanoes brought water vapor, carbon dioxide, nitrogen, sulfur, and sulfur compounds from the planet's interior to its surface. This was critical to the formation of the air we breathe today. Additionally, volcanic activity plays a significant role in the carbon cycle, whereby that vital element is circulated through various earth systems (see Biogeochemical Cycles and Carbon Cycle).

Earth and Venus stand alone among terrestrial planets as the only two still prone to volcanic activity. (By contrast, Mercury and the Moon have long been dead volcanically, and volcanism on Mars seems to have ended at some point during the past billion years.) This is significant, because even though all the planets possess more or less the same chemical elements, volcanoes are critical to distributing those elements.

In addition, volcanic activity, as well as the heat from Earth's interior that drives it and other tectonic phenomena, is an important influence

on the separation of chemical compounds. When Earth formed some 4.5 billion years ago, heavier compounds—among them, those containing iron—sank toward the planet's core. At the same time, lighter ones began to rise into the atmosphere. Among these compounds was oxygen, which is clearly essential to the life of humans and other animals. This separation of compounds continues on Earth, owing to the large amount of heat that emanates from the interior.

GEOTHERMAL ENERGY. One would hardly guess that our atmosphere—or the circulation of carbon, a key component in all lifeforms—could be the indirect product of activity that takes place at least 60 mi.(100 km) below our feet. Nor is this the only illustration of the impact that Earth's interior exerts on our world. The interior of Earth is also responsible for the action that produces geothermal energy, discussed in detail within Energy and Earth.

Geothermal energy provides heating and electricity for several countries and is responsible for the dramatic effect of such phenomena as "Old Faithful" at Yellowstone Park in Wyoming. It is also the source behind the soothing natural springs found in such well-known resorts as Warm Springs, Georgia (a favorite getaway for President Franklin D. Roosevelt, who died there in 1945), and Hot Springs, Arkansas, the hometown of another president, Bill Clinton.

Mesosphere to Inner Core: Geomagnetism and Gravity

After we pass through the base of the asthenosphere, we are still only 155 mi. (250 km) deep. Now we are in the mesosphere, which extends to a depth of 1,800 mi. (2,900 km) and includes several other discontinuities, or thresholds of change. We will not discuss the details of these discontinuities here, except to note that they indicate changes in geochemical composition: for example, at 400 mi. (650 km) there appears to be a marked increase in the ratio of iron to magnesium.

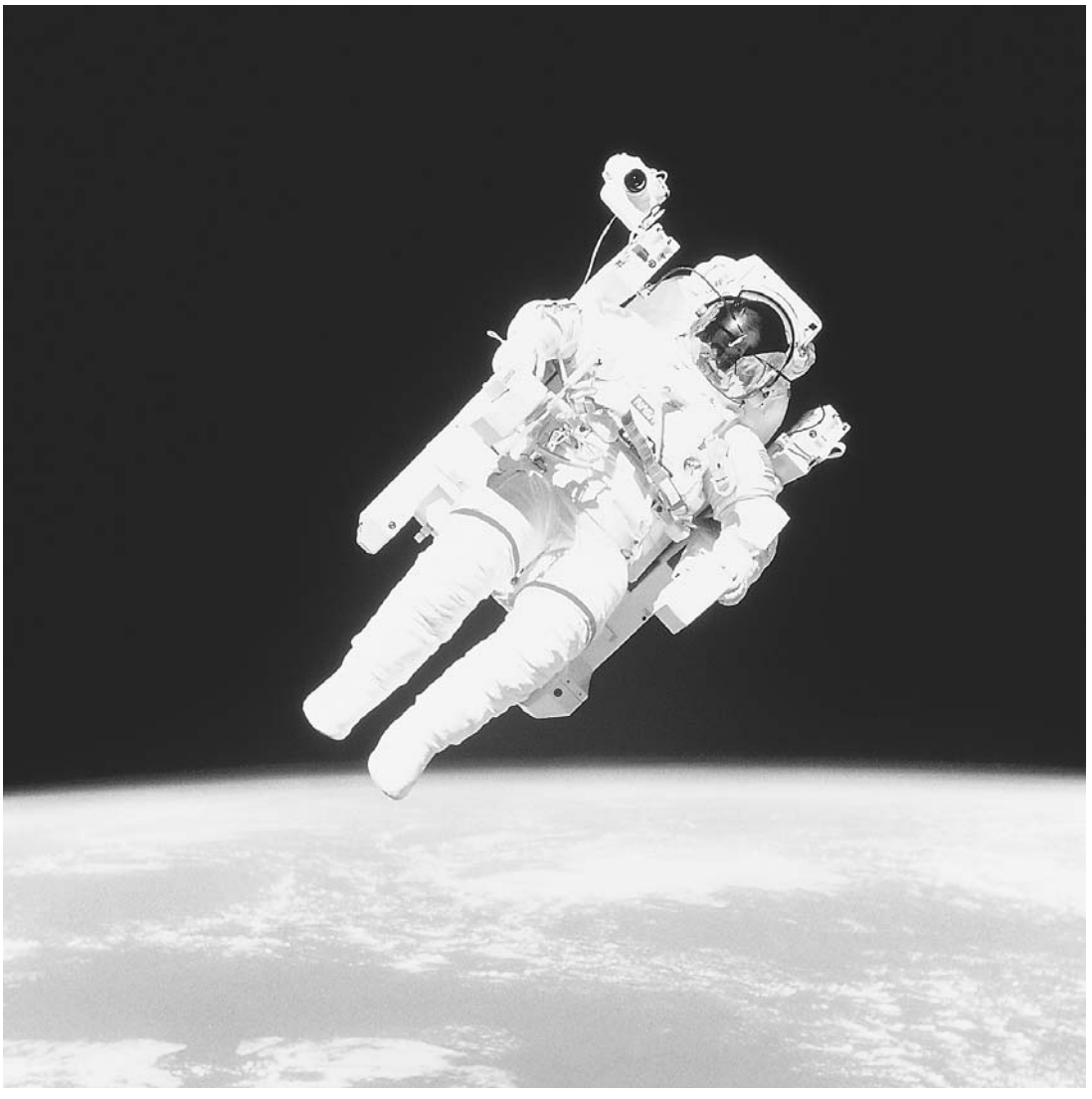
The Gutenberg discontinuity, or the core-mantle boundary (CMB), marks our entrance to the core. By now it has become very, very hot. Whereas the lithospheric mantle is about 1,600°F (870°C), the bottom of the lithosphere is about 4,000–6,700°F (2,200–3,700°C). By the time we get to the inner core, we may be confronted with temperatures as high as 13,000°F (7,200°C)—which, if this is true, would make the center of Earth about 50% hotter than the surface of the Sun!

EARTH'S FIERY HEART. At such temperatures, one would expect the rock of the outer core to be entirely molten, and indeed it is. In fact, it is this difference in phase or state of matter that marks the change from mantle (which is partially solid) to the liquid outer core. The region between the mantle and the outer core is one of undulating boundaries due to convection (see Convection), which may be the driving force behind the plate tectonic activity that occurs at a much higher level. In addition, the eddies and currents of molten iron in the core are ultimately responsible for the planet's magnetic field (see Geomagnetism).

The boundary between the mantle and core is lower today than it once was, a sign that our planet is slowly aging. If there ever comes a point when the heat is entirely dissipated, as may perhaps happen many billions of years from now, that could well be the end of Earth as a "living" planet. If we did not have a mantle and core, with all their heat, pressure, and resulting tectonic activity, Earth would be as dead as the Moon, whose interior is relatively cool.

The distinction between the outer and inner cores, which starts at a depth of about 3,150 mi. (5,100 km), comes from the fact that here, too, there is a phase change—in this case from liquid, molten material back to solid. This has nothing to do with cooling, since, as we have noted, the inner core is almost unimaginably hot; rather, it is a result of the immense pressures apparent at this depth.

GRAVITY ALWAYS WINS. It is interesting to note that the core constitutes only about 16% of the planet's volume but 32% of its mass. As we discussed near the beginning of this essay, enormous gravitational force exists between two objects when at least one of them has a relatively large amount of mass and the distance between them is great. Thus, Earth's mass, concentrated deep in its interior, helps hold our world—people, animals, plants, buildings, and so forth—in place. It also keeps our atmosphere firmly rooted as well. Without an extensive gravitational field of the kind that Earth possesses, significantly less massive bodies, such as the Moon or Mercury, have no atmosphere. In this and many another way, it turns out that life on



The astronaut Bruce McCandless floats freely in space, outside Earth's atmosphere, during a shuttle mission. Earth's vast interior mass gives it a strong gravitational pull, helping root the people and materials of our world and holding our atmosphere in place. *(NASA. Reproduced by permission.)*

Earth's surface depends heavily on what goes on its ultra-hot, extremely pressurized interior.

A Bizarre Postscript

Given the vast amount of power in Earth's interior, it is no wonder that it has long fascinated humans—even before science possessed any sort of intelligent understanding with regard to the contents of that interior. The ancients offered all manner of fascinating speculation regarding the contents of Earth: it was hollow, some said, while others claimed that it contained one substance or another—perhaps even a heart of gold.

Such imaginative musings continued well into the Middle Ages, when the Italian poet Dante Alighieri (1265–1321) described an allegorical journey through Earth's interior in his epochal *Divine Comedy.* This epic poem depicts the inside of the planet as concentric circles of hell, descending toward the fiery core, where Satan himself resides. Beyond this lies Purgatory and further still—on the other side of Earth—Heaven, the New Jerusalem.

By the time the French writer Jules Verne (1828–1905) wrote *Journey to the Center of the Earth* almost six centuries later, scientific knowledge regarding Earth's interior had increased dramatically, though many of the significant discoveries we have examined here—for example, the Moho—still lay in the future. In any case, the

KEY TERMS

ASTHENOSPHERE: A region of extremely high pressure underlying the lithosphere, where rocks are deformed by enormous stresses. The asthenosphere lies at a depth of about 60 mi. to 215 mi. (about 100–350 km).

ATMOSPHERE: In general, an atmosphere is a blanket of gases surrounding a planet. Unless otherwise identified, however, the term refers to the atmosphere of Earth, which consists of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon (0.07%).

CORE: The center of Earth, an area constituting about 16% of the planet's volume and 32% of its mass. Made primarily of iron and another, lighter element (possibly sulfur), it is divided between a solid inner core with a radius of about 760 mi. (1,220 km) and a liquid outer core about 1,750 mi. (2,820 km) thick. For terrestrial planets, in general, core refers to the center, which in most cases is probably molten metal of some kind.

CRUST: The uppermost division of the solid Earth, representing less than 1% of its volume and varying in depth from 3 mi. to 37 mi. (5–60 km). Below the crust is the mantle.

GEOCHEMISTRY: A branch of the earth sciences, combining aspects of geology and chemistry, that is concerned with the chemical properties and processes of Earth—in particular, the abundance and interaction of chemical elements and their isotopes.

GEOLOGY: The study of the solid earth, in particular, its rocks, minerals, fossils, and land formations.

GEOPHYSICS: A branch of the earth sciences that combines aspects of geology and physics. Geophysics addresses the planet's physical processes as well as its gravitational, magnetic, and electric properties and the means by which energy is transmitted through its interior.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

tone of Verne's work was that of a new literary style, science fiction. Pioneered by Verne and the British writer H. G. Wells, science fiction could not have been less like Dante's poetry, infused as it was with spirituality and mystery.

SCREAMS OF THE DAMNED? In the early 1990s, an urban legend of sorts brought together the science fiction of Verne, the religious vision of Dante, and a number of other, less pleasant strains—including ignorance and, on the part of its originators, the willingness to deceive. This "urban legend" did not involve crocodiles in sewers, ghostly hitchhikers, or the other usual fodder; instead, it concerned the center of the earth—where, it was claimed, hell had been discovered.

The full account appeared on Ship of Fools (see "Where to Learn More"), a Web site operated by Rich Buhler—himself a Christian minister and a debunker of what he has called "Christian urban legends." As Buhler reported, the story gained so much support that it appeared on Trinity Broadcasting Network (TBN), a major evangelical television outlet. According to the TBN

KEY TERMS CONTINUED

JOVIAN PLANETS: The planets between Mars (the last terrestrial planet) and Pluto, all of which are large, low in density, and composed primarily of gases.

LITHOSPHERE: The upper layer of Earth's interior, including the crust and the brittle portion at the top of the mantle.

MANTLE: The thick, dense layer of rock, approximately 1,429 mi. (2,300 km) thick, between Earth's crust and its core. In reference to the other terrestrial planets, mantle simply means the area of dense rock between the crust and core.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals) and oxides, such as carbon dioxide.

PLATE TECTONICS: The name both of a theory and of a specialization of tectonics. As an area of study, plate tectonics deals with the large features of the lithosphere and the forces that shape them. As a theory, it explains the processes that have shaped Earth in terms of plates and their movement. Plate tectonics theory brings together aspects of continental drift, seafloor spreading, seismic and volcanic activity, and the structures of Earth's crust to provide a unifying model of Earth's evolution. It is one of the dominant concepts in the modern earth sciences.

PLATES: Large, movable segments of the lithosphere.

SEISMIC WAVE: A packet of energy resulting from the disturbance that accompanies a strain on rocks in the lithosphere.

SEISMOLOGY: The study of seismic waves as well as the movements and vibrations that produce them.

TECTONICS: The study of tectonism, including its causes and effects, most notably mountain building.

TECTONISM: The deformation of the lithosphere.

TERRESTRIAL PLANETS: The four inner planets of the solar system: Mercury, Venus, Earth, and Mars. These are all small, rocky, and dense; have relatively small amounts of gaseous elements; and are composed primarily of metals and silicates. Compare with Jovian planets.

report, Russian geologists had drilled a hole some 8.95 mi. (14.4 km) into Earth's crust and heard screams, which supposedly came from condemned souls in the nether regions.

As the embellished details of the story began to unfold, it turned out that the Russian geologists had found the temperatures to be much higher than expected: 2,000°F (1,093°C). Also, their drilling had unleashed a bat that flew out of hell with the words "I have conquered" inscribed in Russian on its wings. Buhler and his team traced this bizarre tale to Finland and then back to southern California. As to how the story originated, Buhler noted the drilling at the Kola Peninsula, which we mentioned earlier in this essay. The depth cited in the rumor, however, was greater than that which the drilling at Kola reached, and the temperatures claimed were much higher than what one actually would encounter at that depth.

"It is possible that somewhere in the world there has been a spooky experience during deep drilling operations," Buhler concluded. Nonetheless, "characteristic of many urban legends, this

story was alleged to have occurred in an obscure part of the world where it would be virtually impossible to track down the facts. And once the story got started, people began quoting one another's newsletters to validate their own. This is the stuff of which tabloid newspapers are made." In the end, the "screams of hell" offered nothing of value in terms of either science or religion, but it proved to be an excellent example of human beings' fascination with, and latent terror of, Earth's interior.

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PLATE TECTONICS

CONCEPT

The earth beneath our feet is not dead; it is constantly moving, driven by forces deep in its core. Nor is the planet's crust all of one piece; it is composed of numerous plates, which are moving steadily in relation to one another. This movement is responsible for all manner of phenomena, including earthquakes, volcanoes, and the formation of mountains. All these ideas, and many more, are encompassed in the concept of plate tectonics, which is the name for a branch of geologic and geophysical study and for a powerful theory that unites a vast array of ideas. Plate tectonics works hand in hand with several other striking concepts and discoveries, including continental drift and the many changes in Earth's magnetic field that have taken place over its history. No wonder, then, that this idea, developed in the 1960s but based on years of research that preceded that era, is described as "the unifying theory of geology."

HOW IT WORKS

Tectonics and Tectonism

The lithosphere is the upper layer of Earth's interior, including the crust and the brittle portion at the top of the mantle. Tectonism is the deformation of the lithosphere, and the term tectonics refers to the study of this deformation, including its causes and effects, most notably mountain building. This deformation is the result of the release and redistribution of energy from Earth's core.

The interior of Earth itself is divided into three major sections: the crust, mantle, and core. The first is the uppermost division of the solid earth, representing less than 1% of its volume and varying in depth from 3 mi. to 37 mi. (5–60 km). Below the crust is the mantle, a thick, dense layer of rock approximately 1,429 mi. (2,300 km) thick. The core itself is even more dense, as illustrated by the fact that it constitutes about 16% of the planet's volume and 32% of its mass. Composed primarily of iron and another, lighter element (possibly sulfur), it is divided between a solid inner core with a radius of about 760 mi. (1,220 km) and a liquid outer core about 1,750 mi. (2,820 km) thick.

Tectonism results from the release and redistribution of energy from Earth's interior. There are two components of this energy: gravity, a function of the enormous mass at the core, and heat from radioactive decay. (For more about gravity, see Gravity and Geodesy. The heat from Earth's core, the source of geothermal energy, is discussed in Energy and Earth.) Differences in mass and heat within the planet's interior, known as pressure gradients, result in the deformation of rocks.

DEFORMATION OF ROCKS. Any attempt to deform an object is referred to as stress, and stress takes many forms, including tension, compression, and shear. Tension acts to stretch a material, whereas compression—a type of stress produced by the action of equal and opposite forces, whose effect is to reduce the length of a material—has the opposite result. (Compression is a form of pressure.) As for shear, this is a kind of stress resulting from equal and opposite forces that do not act along the same line. If a thick, hardbound book is lying flat and one pushes the front cover from the side so

that the covers and pages are no longer perfectly aligned, this is an example of shear.

Under the effects of these stresses, rocks may bend, warp, slide, or break. They may even flow, as though they were liquids, or melt and thus truly become liquid. As a result, Earth's interior may manifest faults, or fractures in rocks, as well as folds, or bends in the rock structure. The effects of this activity can be seen on the surface in the form of subsidence, which is a depression in the crust, or uplift, which is the raising of crustal materials. Earthquakes and volcanic eruptions also may result.

There are two basic types of tectonism: orogenesis and epeirogenesis. *Orogenesis* is taken from the Greek words *oros* ("mountain") and *genesis* ("origin") and involves the formation of mountain ranges by means of folding, faulting, and volcanic activity. The Greek word *epeiros* means "mainland," and epeirogenesis takes the form of either uplift or subsidence. Of principal concern in the theory of plate tectonics, as we shall see, is orogenesis, which involves more lateral, as opposed to vertical, movement.

Continental Drift

If one studies a world map for a period of time, one may notice something interesting about the shape of Africa's west coast and that of South America's east coast: they seem to fit together like pieces of a jigsaw puzzle. Early in the twentieth century, two American geologists, Frank Bursley Taylor (1860–1938) and Howard Baker, were among the first scientists to point out this fact. According to Taylor and Baker, Europe, the Americas, and Africa all had been joined at one time. This was an early version of continental drift, a theory concerning the movement of Earth's continents.

Continental drift is based on the idea that the configuration of continents was once different than it is today, that some of the individual landmasses of today once were joined in other continental forms, and that the landmasses later moved to their present locations. Though Taylor and Baker were early proponents, the theory is associated most closely with the German geophysicist and meteorologist Alfred Wegener (1880–1930), who made the case for continental drift in *The Origin of Continents and Oceans* (1915).

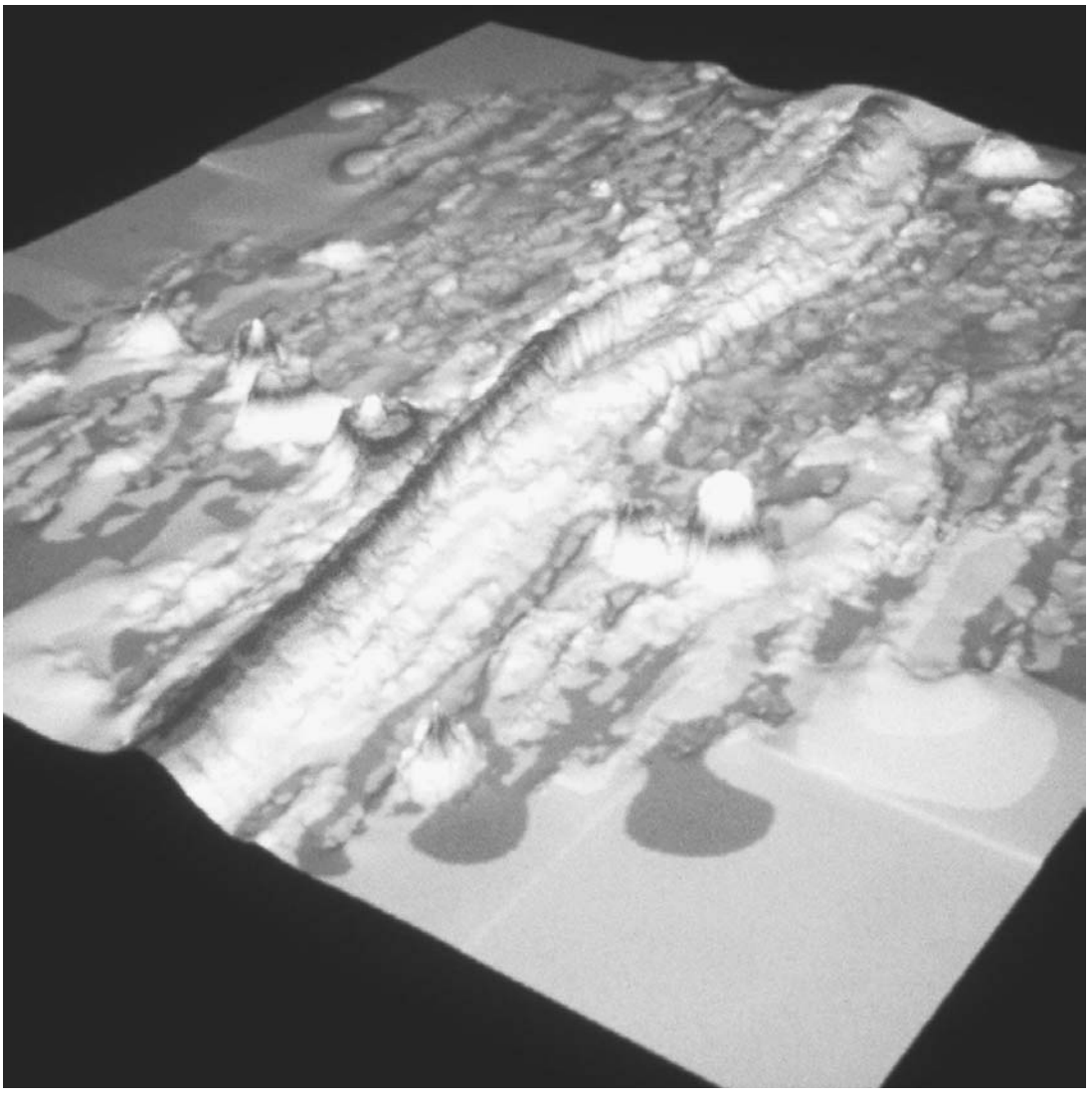
PANGAEA, LAURASIA, AND GONDWANALAND. According to Wegener, the continents of today once formed a single supercontinent called Pangaea, from the Greek words *pan* ("all") and *gaea* ("Earth"). Eventually, Pangaea split into two halves, with the northern continent of Laurasia and the southern continent of Gondwanaland, sometimes called Gondwana, separated by the Tethys Sea. In time, Laurasia split to form North America, the Eurasian landmass with the exception of the Indian subcontinent, and Greenland. Gondwanaland also split, forming the major southern landmasses of the world: Africa, South America, Antarctica, Australia, and India.

The Austrian geologist Eduard Suess (1831–1914) and the South African geologist Alexander du Toit (1878–1948), each of whom contributed significantly to continental drift theory, were responsible for the naming of Gondwanaland and Laurasia, respectively. Suess preceded Wegener by many years with his theory of Gondwanaland, named after the Gondwana region of southern India. There he found examples of a fern that, in fossilized form, had been found in all the modern-day constituents of the proposed former continent. Du Toit, Wegener's contemporary, was influenced by continental drift theory and improved on it greatly.

FORMATION OF THE CONTINENTS. Today continental drift theory is accepted widely, in large part owing to the development of plate tectonics, "the unifying theory in geology." We examine the evidence for continental drift, the arguments against it, and the eventual triumph of plate tectonics in the course of this essay. Before going on, however, let us consider briefly the now-accepted timeline of events described by Wegener and others.

About 1,100 million years ago (earth scientists typically abbreviate this by using the notation 1,100 Ma), there was a supercontinent named Rodinia, which predated Pangaea. It split into Laurasia and Gondwanaland, which moved to the northern and southern extremes of the planet, respectively. Starting at about 514 Ma, Laurasia drifted southward until it crashed into Gondwanaland about 425 Ma. Pangaea, surrounded by a vast ocean called Panthalassa ("All Ocean"), formed approximately 356 Ma.

In the course of Pangaea's formation, what is now North America smashed into northwestern



A MAP OF PART OF THE EAST PACIFIC RISE, A MID-OCEAN RIDGE TO THE WEST OF CENTRAL AMERICA THAT MARKS THE BOUNDARY BETWEEN THE PACIFIC AND COCOS TECTONIC PLATES. *(© Dr. Ken MacDonald/Photo Researchers. Reproduced by permission.)*

Africa, forming a vast mountain range. Traces of these mountains still can be found on a belt stretching from the southern United States to northern Europe, including the Appalachians. As Pangaea drifted northward and smashed into the ocean floor of Panthalassa, it formed a series of mountain ranges from Alaska to southern South America, including the Rockies and Andes. By about 200 Ma, Pangaea began to break apart, forming a valley that became the Atlantic Ocean. But the separation of the continents was not a "neat" process: today a piece of Gondwanaland lies sunken beneath the eastern United States, far from the other landmasses to which it once was joined.

By about 152 Ma, in the late Jurassic period, the continents as we know them today began to take shape. By about 65 Ma, all the present continents and oceans had been formed for the most part, and India was drifting north, eventually smashing into southern Asia to shape the world's tallest mountains, the Himalayas, the Karakoram Range, and the Hindu Kush. This process is not finished, however, and geologists believe that some 250–300 million years from now, Pangaea will re-form.

EVIDENCE AND ARGUMENTS. As proof of his theory, Wegener cited a wide variety of examples, including the apparent fit between the coastlines of South America and

western Africa as well as that of North America and northwestern Africa. He also noted the existence of rocks apparently gouged by glaciers in southern Africa, South America, and India, far from modern-day glacial activity. Fossils in South America matched those in Africa and Australia, as Suess had observed. There were also signs that mountain ranges continued between continents—not only those apparently linking North America and Europe but also ranges that seemed to extend from Argentina to South Africa and Australia.

By measurements conducted over a period of years, Wegener even showed that Greenland was drifting slowly away from Europe, yet his theory met with scorn from the geoscience community of his day. If continents could plow through oceanic rock, some geologists maintained, then they would force up mountains so high that Earth would become imbalanced. As for his claim that matching fossils in widely separated regions confirmed his theory of continental drift, geologists claimed that this could be explained by the existence of land bridges, now sunken, that once had linked those areas. The apparent fit between present-day landmasses could be explained away as coincidence or perhaps as evidence that Earth simply was expanding, with the continents moving away from one another as the planet grew.

Introduction to Plate Tectonics

Though Wegener was right, as it turned out, his theory had one major shortcoming: it provided no explanation of exactly *how* continental drift had occurred. Even if geologists had accepted his claim that the continents are moving, it raised more questions than answers. A continent is a very large thing simply to float away; even an aircraft carrier, which is many millions of times lighter, has to weigh less than the water it displaces, or it would sink like a stone. In any case, Wegener never claimed that continents floated. How, then, did they move?

The answer is plate tectonics, the name both of a theory and of a specialization of tectonics. As an area of study, plate tectonics deals with the large features of the lithosphere and the forces that fashion them. As a theory, it explains the processes that have shaped Earth in terms of plates (large movable segments of the lithosphere) and their movement. Plate tectonics theory brings together aspects of continental drift, seafloor spreading (discussed later), seismic and volcanic activity, and the structures of Earth's crust to provide a unifying model of Earth's evolution.

It is hard to overemphasize the importance of plate tectonics in the modern earth sciences; hence, its characterization as the "unifying theory." Its significance is demonstrated by its inclusion in the book *The Five Biggest Ideas of Science,* cited in the bibliography for this essay. Alongside plate tectonics theory in that volume are four towering concepts of extraordinary intellectual power: the atomic model, or the concept that matter is made up of atoms; the periodic law, which explains the chemical elements; big bang theory, astronomers' explanation of the origins of the universe (see Planetary Science); and the theory of evolution in the biological sciences.

THE PIECES COME TOGETHER. In 1962 the United States geologist Harry Hammond Hess (1906–1969) introduced a new concept that would prove pivotal to the theory of plate tectonics: seafloor spreading, the idea that seafloors crack open along the crest of mid-ocean ridges and that new seafloor forms in those areas. (Another American geologist, Robert S. Dietz [1914–1995], had published his own theory of seafloor spreading a year before Hess's, but Hess apparently developed his ideas first.) According to Hess, a new floor forms when molten rock called magma rises up from the asthenosphere, a region of extremely high pressure underlying the lithosphere, where rocks are deformed by enormous stresses. The magma wells up through a crack in a ridge, runs down the sides, and solidifies to form a new floor.

Three years later, the Canadian geologist John Tuzo Wilson (1908–1993) coined the term plates to describe the pieces that make up Earth's rigid surface. Separated either by the mid-ocean rifts identified earlier by Heezen or by mountain chains, the plates move with respect to one another. Wilson presented a model for their behavior and established a global pattern of faults, a sort of map depicting the movable plates. The pieces of a new theory were forming (an apt metaphor in this instance!), but as yet it had no name.

That name appeared in 1967, when D. P. Mackenzie of England and R. L. Parker of the

United States introduced the term plate tectonics. They maintained that the surface of Earth is divided into six major as well as seven minor movable plates and compared the continents to enormous icebergs—much as Wegener had described them half a century earlier. Subsequent geologic research has indicated that there may be as many as nine major plates and as many as 12 minor ones.

To test these emerging ideas, the U.S. National Science Foundation authorized a research voyage by the vessel *Glomar Challenger* in 1968. On their first cruise, through the Gulf of Mexico and the Atlantic, the *Challenger*'s scientific team collected sediment, fossil, and crust samples that confirmed the basics of seafloor spreading theory. These results led to new questions regarding the reactions between rocks and the heated water surrounding them, spawning new research and necessitating additional voyages. In the years that followed, the *Challenger* made more and more cruises, its scientific teams collecting a wealth of evidence for the emerging theory of plate tectonics.

REAL-LIFE APPLICATIONS

Early Evidence of Plate Tectonics

No single person has been as central to plate tectonics as Wegener was to continental drift or as the English naturalist Charles Darwin (1809–1882) was to evolution. The roots of plate tectonics lie partly in the observations of Wegener and other proponents of continental drift as well as in several discoveries and observations that began to gather force in the third quarter of the twentieth century.

During World War II, submarine warfare necessitated the development of new navigational technology known as sonar (*SO*und *N*avigation *A*nd *R*anging). Sonar functions much like radar (see Remote Sensing), but instead of using electromagnetic waves, it utilizes ultrasonic, or high-frequency, sound waves projected through water. Sonar made it feasible for geologists to study deep ocean basins after the war, making it possible for the first time in history to map and take samples from large areas beneath the seas. These findings raised many questions, particularly concerning the vast elevation differences beneath the seas.

EWING AND THE MOUNTAINS UNDER THE OCEAN. One of the first earth scientists to notice the curious aspects of underwater geology was the American geologist William Maurice Ewing (1906–1974), who began his work long before the war. He had gained his first experience in a very practical way during the 1920s, as a doctoral student putting himself through school. Working summers with oil exploration teams in the Gulf of Mexico off the coast of Texas had given him a basic understanding of the subject, and in the following decade he went to work exploring the structure of the Atlantic continental shelf and ocean basins.

His work there revealed extremely thick sediments covering what appeared to be high mountainous regions. These findings sharply contradicted earlier ideas about the ocean floor, which depicted it as a flat, featureless plain rather like the sandy-bottomed beaches found in resort areas. Instead, the topography at the bottom of the ocean turned out to be at least as diverse as that of the land above sea level.

HEEZEN AND THE RIFT VALLEY. During the 1950s, a team led by another American geologist, Bruce Charles Heezen (1924–1977), worked on developing an overall picture of the ocean basin's topography. Earlier work had identified a mountain range running the length of the Atlantic, but Heezen's team discovered a deep valley down the middle of the chain, running parallel to it. They described it as a rift valley, a long trough bounded by two or more faults, and compared it to a similar valley in eastern Africa.

Around the same time, a group of transatlantic telephone companies asked Heezen to locate areas of possible seismic or earthquake activity in the Atlantic. Phone company officials reasoned that if they could find the areas most likely to experience seismic activity, they could avoid placing their cables in those areas. As it turned out, earthquakes tended to occur in exactly the same region that Heezen and his team had identified as the rift valley.

The Plates and Their Interactions

The most significant plates that make up Earth's surface are as follows:

Selected Major Plates

- North American (almost all of North America and Mexico, along with Greenland and the northwestern quadrant of the Atlantic)
- South American (all of South America and the southwestern quadrant of the Atlantic)
- African (Africa, the southeastern Atlantic, and part of the Indian Ocean)
- Eurasian (Europe and Asia, excluding the Indian subcontinent, along with surrounding ocean areas)
- Indo-Australian (India, much of the Indian Ocean, Australia, and parts of the Indonesian archipelago and New Zealand)
- Antarctic (Antarctica and the Antarctic Ocean)

In addition to these plates, there are several plates that while they are designated as "major" are much smaller: the Philippine, Arabian, Caribbean, Nazca (off the west coast of South America), Cocos (off the west coast of Mexico), and Juan de Fuca (extreme western North America). Japan, one of the most earthquake-prone nations in the world, lies at the nexus of the Philippine, Eurasian, and Pacific plates.

MOVEMENT OF THE PLATES. One of the key principles of geology, discussed elsewhere in this book, is uniformitarianism: the idea that processes occurring now also occurred in the past. The reverse usually is also true; thus, as we have noted, the plates are still moving, just as they have done for millions of years. Thanks to satellite remote sensing, geologists are able to measure this rate of movement. (See Remote Sensing for more on this subject.) Not surprisingly, its pace befits the timescale of geologic, as opposed to human, processes: the fastest-moving plates are careening forward at a breathtaking speed of 4 in. (10 cm) per year. The ground beneath Americans' feet (assuming they live in the continental United States, east of the Juan de Fuca) is drifting at the rate of 1.2 in. (3 cm) every year, which means that in a hundred years it will have shifted 10 ft. (3 m).

WHEN PLATES INTERACT. Plates interact by moving toward each other (convergence), away from each other (divergence), or past each other (transform motion). Convergence usually is associated with subduction, meaning that one plate is forced down into the mantle and eventually undergoes partial melting. This typically occurs in the ocean, creating a depression known as an oceanic trench. Divergence results in the separation of plates and most often is associated either with seafloor spreading or the formation of rift valleys.

There are three types of plate margins, or boundaries between plates, depending on the two types of crusts that are interacting: oceanic with oceanic, continental with continental, or continental with oceanic. The rift valleys of the Atlantic are an example of an oceanic margin where divergence has occurred, while oceanic convergence is illustrated by a striking example in the Pacific. There, subduction of the Philippine Plate by the Pacific Plate has created the Mariana Trench, which at 36,198 ft. (10,911 m) is the deepest depression on Earth.

When continental plates converge, neither plate subducts; rather, they struggle against each other like two warriors in a fight to the death, buckling, folding, and faulting to create huge mountain ranges. The convergence of the Indo-Australian and Eurasian plates has created the *highest* spots on Earth, in the Himalayas, where Mount Everest (on the Nepal-Indian border) rises to 29,028 ft. (8,848 m). Continental plates also may experience divergence, resulting in the formation of seas. An example is the Red Sea, formed by the divergence of the African and Arabian plates.

Given these facts about the interactions of oceanic and continental plates with each other, what occurs when continental plates meet oceanic ones is no surprise. In this situation, the oceanic plate meeting the continental plate is like a high-school football player squaring off against a National Football League pro tackle. It is no match: the oceanic plate easily subducts. This leads to the formation of a chain of volcanoes along the continental crust, examples being the Cascade Range in the U.S. Pacific Northwest (Juan de Fuca and Pacific plates) or the Andes (South American and Nazca plates).

Transform margins may occur with any combination of oceanic or continental plates and result in the formation of faults and earthquake zones. Where the North American Plate slides against the Pacific Plate along the California coast, it has formed the San Andreas Fault, the source of numerous earthquakes, such as the dramatic San Francisco quakes of 1906 and 1989 and the Los Angeles quake of 1994.



Shuttle photograph of eastern Egypt shows the Red Sea at the top, with the Gulf of Suez connecting it to the Mediterranean Sea. The Red Sea was formed by the divergence of the African and Arabian plates. *(© NASA/Photo Researchers. Reproduced by permission.)*

Paleomagnetism

As noted earlier, plate tectonics brings together numerous areas of study in the geologic sciences that developed independently but which came to be seen as having similar roots and explanations. Among these disciplines is paleomagnetism, an area of historical geology devoted to studying the direction and intensity of magnetic fields in the past, as discerned from the residual magnetization of rocks.

Earth has a complex magnetic field whose principal source appears to be the molten iron of the outer core. In fact, the entire planet is like a giant bar magnet, with a north pole and a south pole. It is for this reason that the magnetized material in a compass points north; however, Earth's magnetic north pole is not the same as its geographic north pole. It so happens that magnetic north lies in more or less the same direction as geographic north, but as geologists in the mid–nineteenth century discovered, this has not always been the case. (For more about magnetic north and other specifics of Earth's magnetic field, see Geomagnetism.)

In 1849 the French physicist Achilles Delesse (1817–1881) observed that magnetic minerals tend to line up with the planet's magnetic field, pointing north as though they were compass needles. Nearly 60 years later, however, another French physicist, Bernard Brunhes (1867–1910),

KEY TERMS

ASTHENOSPHERE: A region of extremely high pressure underlying the lithosphere, where rocks are deformed by enormous stresses. The asthenosphere lies at a depth of about 60-215 mi. (about 100–350 km).

COMPRESSION: A form of stress produced by the action of equal and opposite forces, the effect of which is to reduce the length of a material. Compression is a form of pressure.

CONTINENTAL DRIFT: The theory that the configuration of Earth's continents was once different than it is today; that some of the individual landmasses of today once were joined in other continental forms; and that these landmasses later separated and moved to their present locations.

CONVERGENCE: A tectonic process whereby plates move toward each other. Usually associated with subduction, convergence typically occurs in the ocean, creating an oceanic trench. It is one of the three ways, along with divergence and transform motion, that plates interact.

CORE: The center of Earth, an area constituting about 16% of the planet's volume and 32% of its mass. Made primarily of iron and another, lighter element (possibly sulfur), it is divided between a solid inner core with a radius of about 760 mi. (1,220 km) and a liquid outer core about 1,750 mi. (2,820 km) thick.

CRUST: The uppermost division of the solid earth, representing less than 1% of its volume and varying in depth from 3-37 mi. (5–60 km). Below the crust is the mantle.

DIVERGENCE: A tectonic process whereby plates move away from each other. Divergence results in the separation of plates and is associated most often either with seafloor spreading or with the formation of rift valleys. It is one of the three ways, along with convergence and transform motion, that plates interact.

EPEIROGENESIS: One of two principal forms of tectonism, the other being orogenesis. Derived from the Greek words *epeiros* ("mainland") and *genesis* ("origins"), epeirogenesis takes the form of either uplift or subsidence.

FAULT: An area of fracturing between rocks resulting from stress.

FOLD: An area of rock that has been bent by stress.

GEOPHYSICS: A branch of the earth sciences that combines aspects of geology and physics. Geophysics addresses the planet's physical processes as well as its gravitational, magnetic, and electric properties, and the means by which energy is transmitted through its interior.

HISTORICAL GEOLOGY: The study of Earth's physical history. Historical geology is one of two principal branches of geology, the other being physical geology.

LITHOSPHERE: The upper layer of Earth's interior, including the crust and the brittle portion at the top of the mantle.

MA: An abbreviation used by earth scientists, meaning "million years." When an event is designated as, for instance, 160 Ma, it means that it happened 160 million years ago.

MANTLE: The thick, dense layer of rock, approximately 1,429 mi. (2,300 km) thick, between Earth's crust and its core.

KEY TERMS CONTINUED

MID-OCEAN RIDGES: Submarine mountain ridges where new seafloor is created by seafloor spreading.

OCEANIC TRENCH: A deep depression in the ocean floor caused by the convergence of plates and the resulting subduction of one plate.

OROGENESIS: One of two principal forms of tectonism, the other being epeirogenesis. Derived from the Greek words *oros* ("mountain") and *genesis* ("origin"), orogenesis involves the formation of mountain ranges by means of folding, faulting, and volcanic activity. The processes of orogenesis play a major role in plate tectonics.

PALEOMAGNETISM: An area of historical geology devoted to studying the direction and intensity of magnetic fields in the past, as discerned from the residual magnetization of rocks.

PLATE MARGINS: Boundaries between plates.

PLATE TECTONICS: The name both of a theory and of a specialization of tectonics. As an area of study, plate tectonics deals with the large features of the lithosphere and the forces that fashion them. As a theory, it explains the processes that have shaped Earth in terms of plates and their movement. Plate tectonics theory brings together aspects of continental drift, seafloor spreading, seismic and volcanic activity, and the structures of Earth's crust to provide a unifying model of Earth's evolution. It is one of the dominant concepts in the modern earth sciences.

PLATES: Large movable segments of the lithosphere.

RADIOACTIVITY: A term describing a phenomenon whereby certain materials are subject to a form of decay brought about by the emission of high-energy particles or radiation. Forms of particles or energy include alpha particles (positively charged helium nuclei), beta particles (either electrons or subatomic particles called *positrons*), or gamma rays, which occupy the highest energy level in the electromagnetic spectrum.

REMOTE SENSING: The gathering of data without actual contact with the materials or objects being studied.

RIFT: A split between two bodies (for example, two plates) that once were joined.

RIFT VALLEY: A long trough bounded by two or more faults.

SEAFLOOR SPREADING: The theory that seafloors crack open along the crests of mid-ocean ridges and that new seafloor forms in those areas.

SHEAR: A form of stress resulting from equal and opposite forces that do not act along the same line. If a thick, hardbound book is lying flat and one pushes the front cover from the side so that the covers and pages are no longer perfectly aligned, this is an example of shear.

STRESS: In general terms, any attempt to deform a solid. Types of stress include tension, compression, and shear. More specifically, stress is the ratio of force to unit area F/A, where F is force and A area.

SUBDUCTION: A tectonic process that results when plates converge and one plate forces the other down into Earth's mantle. As a result, the subducted plate eventually undergoes partial melting.

KEY TERMS CONTINUED

SUBSIDENCE: A depression in Earth's crust.

TECTONICS: The study of tectonism, including its causes and effects, most notably mountain building.

TECTONISM: The deformation of the lithosphere.

TENSION: A form of stress produced by a force that acts to stretch a material.

THEORY: A general statement derived from a hypothesis that has withstood sufficient testing.

TRANSFORM MOTION: A tectonic process whereby plates slide past each other. It is one of the three ways, along with convergence and divergence, that plates interact.

noted that in some rocks magnetic materials point *south.* This suggested one of two possibilities: either the planet's magnetic field had reversed itself over time, or the ground containing the magnetized rocks had moved. Both explanations must have seemed far-fetched at the time, but as it turned out, both are correct.

Earth's magnetic field has shifted, meaning that the magnetic north and south poles have changed places many times over the eons. In addition, the magnetic poles have wandered around the southern and northern portions of the globe: for instance, whereas magnetic north today lies in the frozen islands to the north of Canada, at about 300 Ma it was located in eastern Siberia. The movement of magnetic rocks on Earth's surface, however, has turned out to be too great to be explained either by magnetic shifts or by regional wandering of the poles. This is where plate tectonics and paleomagnetism come together.

CONFIRMATION OF PLATE TECTONIC THEORY. Rocks in Alaska have magnetic materials aligned in such a way that they once must have been at or near the equator. In addition, the orientation of magnetic materials on South America's east coast shows an affinity with that of similar materials on the west coast of Africa. In both cases, continental drift, with its driving mechanism of plate tectonics, seems the only reasonable explanation.

Thus, paleomagnetic studies have served to confirm the ideas of continental drift and plate tectonics, while research conducted at sea bolsters seafloor spreading theory. Using devices called magnetometers, geologists have found that the orientation of magnetic minerals on one side of a rift mirrors that of materials on the other side. This suggests that the new rock on either side of the rift was formed simultaneously, as seafloor spreading theory indicates.

EARTHQUAKES AND VOLCANOES

Several findings relating to earthquakes and volcanic activity also can be explained by plate tectonics. If one follows news stories of earthquakes, one may begin to wonder why such places as California or Japan have so many quakes, whereas the northeastern United States or western Europe have so few. The fact is that earthquakes occur along belts, and the vast majority of these belts coincide with the boundaries between Earth's major tectonic plates.

The same is true of volcanoes, and it is no mistake that places famous for earthquakes—the Philippines, say, or Italy—often also are known for their volcanoes. Although they are located near the center of the Pacific Plate, the islands of Hawaii are subject to plate movement, which has helped generate the volcanoes that gave those islands their origin. At the southern end of the island chain, many volcanoes are still active, while those at the northern end tend to be dormant. The reason is that the Pacific Plate as a whole is moving northward over a stationary lava source in the mantle below Hawaii. The southern islands remain poised above that source, while the northern islands have moved away from it.

The Oceanic and Continental Crusts

Given what we have seen about continental drift and seafloor spreading, it should come as no surprise to learn that, generally speaking, the deeper one goes in the ocean, the newer the crust. Specifically, the crust is youngest near the center of ocean basins and particularly along mid-ocean ridges, or submarine mountain ridges where new seafloor is created by seafloor spreading.

It also should not be surprising to learn that oceanic and continental crusts differ both in thickness and in composition. Basalt, an igneous rock (rock formed from the cooling of magma), makes up the preponderance of ocean crust, whereas much of the continental crust is made up of granite, another variety of igneous rock. Whereas the ocean crust is thin, generally 3–6 mi. (5–10 km) in depth, the continental crust ranges in thickness from 12.5–55 mi. (20–90 km). This results in a difference in thickness for the lithosphere, which is only about 60 mi. (100 km) thick beneath the oceans but about 2.5 times as thick—150 mi. (250 km)—under the continents.

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SEISMOLOGY

CONCEPT

Disturbances within Earth's interior, which is in a constant state of movement, result in the release of energy in packets known as seismic waves. An area of geophysics known as seismology is the study of these waves and their effects, which often can be devastating when experienced in the form of earthquakes. The latter do not only take lives and destroy buildings, but they also produce secondary effects, most often in the form of a tsunami, or tidal wave. Using seismographs and seismometers, seismologists study earthquakes and other seismic phenomena, including volcanoes and even explosions resulting from nuclear testing. They measure earthquakes according to their magnitude or energy as well as their intensity or human impact. Seismology also is used to study Earth's interior, about which it has revealed a great deal.

HOW IT WORKS

Stress and Strain in Earth's Interior

Modern earth scientists' studies in seismology, as in many other areas, are informed by plate tectonics, and to understand the causes of earthquakes and volcanoes, it is necessary to understand the basics of tectonics as well as plate tectonics theory. The latter subject is discussed in depth within a separate essay, which the reader is encouraged to consult for a more detailed explanation of concepts covered briefly here.

The term tectonism refers to deformation of the lithosphere, the upper layer of Earth's interior. Tectonics is the study of this deformation, which results from the release and redistribution of energy from Earth's core. The core is an extremely dense region, composed primarily of iron and another, lighter element (possibly sulfur), and is divided between a solid inner core with a radius of about 760 mi. (1,220 km) and a liquid outer core about 1,750 mi. (2,820 km) thick.

Earth's core possesses enormous energy, both gravitational and thermal. Gravitational energy is a result of the core's great mass (see Gravity and Geodesy for more about the role of mass in gravity), while thermal energy results from the radioactive decay of elements. In the context of radioactivity, decay does not mean "rot" rather, it refers to the release of high-energy particles. The release of these particles results in the generation of thermal energy, commonly referred to as heat. (See Energy and Earth for more about the scientific definition of heat as well as a discussion of geothermal energy.)

Differences in mass and temperature within the planet's interior, known as pressure gradients, result in the deformation of rocks in the lithosphere. The lithosphere includes the brittle upper portion of the mantle, a dense layer of rock approximately 1,429 mi. (2,300 km) thick, as well as the crust, which varies in depth from 3 mi. to 37 mi. (5–60 km). Deformation is the result of stress—that is, tension (stretching), compression, or shear. (The last of these stresses results from equal and opposite forces that do not act along the same line. To visualize shear, one need only imagine a thick hardbound book with its front cover pushed from the side so that the covers and pages are no longer perfectly aligned.)



A chasm along a fault scarp in San Bernardino County, California. *(© Ken M. Johns/Photo Researchers. Reproduced by permission.)*

Under the effects of these stresses, rocks experience strain, or a change in dimension as they bend, warp, slide, break, flow as though they were liquids, or melt. This strain, in turn, leads to a release of energy in the form of seismic waves. These waves may cause faults, or fractures, as well as folds, or bends in the rock structure, which manifest on the surface in the form of earthquakes, volcanoes, and other varieties of seismic activity. Seismology is the study of these waves as well as the movements and vibrations that produce them.

Continental Drift and Plate Tectonics

The theory of continental drift, discussed in Plate Tectonics, is based on the idea that the configuration of Earth's continents was once different than it is today. Integral to this theory is the accompanying idea that some of the individual land masses of today once were joined in other continental forms and that the land masses later moved to their present locations.

Continental drift theory was introduced in 1915 by the German geophysicist and meteorologist Alfred Wegener (1880–1930), but it failed to gain acceptance for half a century, in large part because it offered no explanation as to how the continents drifted. That explanation came in the 1960s with the development of plate tectonics, the name both of a theory and of a specialization of tectonics. As an area of study, plate tectonics deals with the large features of the lithosphere and the forces that shape them. As a theory, it explains the processes that have shaped Earth in terms of plates (large movable segments of the lithosphere) and their movement.

THE PLATES AND SEISMIC ACTIVITY. There are several major plates, some of which are listed in Plate Tectonics. That essay also discusses modern theories regarding the means by which continents broke apart many millions of years ago and then drifted back together, slamming into one another to form a number of notable features, such as the high mountains between the Indian subcontinent and the Eurasian landmass. Nor have the continents stopped moving; they continue to do so, though at a rate too slow to be noticed in a lifetime or even over the course of several generations. Based on its current rate of movement, in another 6,000 years—approximately the span of time since human civilization began—North America will have drifted about 600 ft. (183 m).

For the most part, the continents we know today are composed of single plates. For instance, South America sits on its own plate, which includes the southwestern quadrant of the Atlantic. But there are exceptions, an example being India itself, which is part of the Indo-Australian plate. Also notable is the Juan de Fuca Plate, a small portion of land attached to the North American continent and comprising the region from northern California to southern British Columbia.

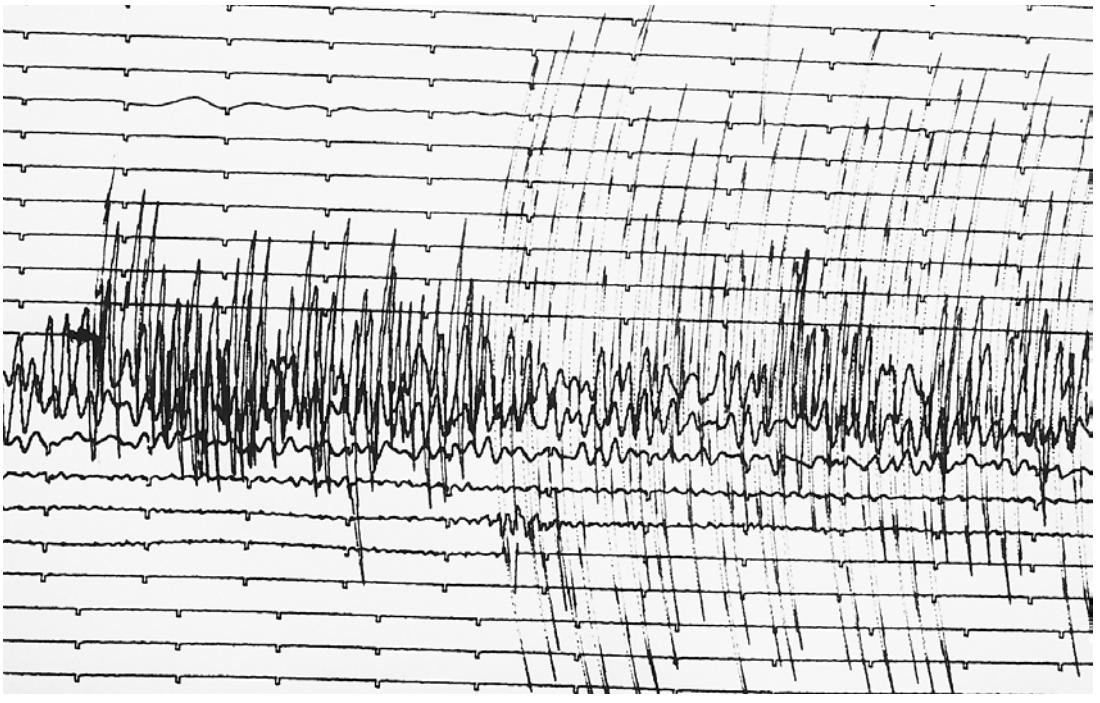
It so happens that this area is home to an unusual amount of volcanic activity. Southern California, where the North American and Pacific plates meet on the San Andreas fault, also is extremely prone to earthquakes, as is Japan, whose islands straddle the Philippine, Eurasian, and Pacific plates. Hawaii is another site of seismic activity in the form of volcanoes, but it does not lie at the nexus of any major plates. Instead, it is situated squarely atop the Pacific Plate, which is moving northward over a hot spot, a region of high volcanic activity. The hot spot remains more or less stationary, while the Pacific Plate moves across it; this explains why the volcanoes of northern Hawaii are generally dormant, whereas many volcanoes in the southern part of the island chain are still active.

Plates interact by moving toward each other (convergence), away from each other (divergence), or past each other (transform motion). When a continental plate converges with an oceanic plate (the differences between these types are discussed in Plate Tectonics), the much sturdier continental plate plows over the oceanic one. This is called subduction. The subducted plate undergoes partial melting, leading to the formation of volcanic chains, as in the nexus of the Juan de Fuca and Pacific or the South American and Nazca plates. The subduction of the Nazca Plate, which lies to the west of South America, helped form the Andes. Transform margins result in the formation of faults and earthquake zones, an example being the volatile San Andreas Fault.

Seismic Waves

The first scientific description of seismic waves was that of John William Strutt, Baron Rayleigh (1842–1919), who in 1885 characterized them as having aspects both of longitudinal and of transverse waves. These are, respectively, waves in which the movement of vibration is in the same direction as the wave itself and those in which the vibration or motion is perpendicular to the direction in which the wave is moving. (Ocean waves, for example, are longitudinal, whereas sound waves are transverse.)

Rayleigh waves later would be distinguished from Love waves, named after the English mathematician and geophysicist Augustus Edward Hough Love (1863–1940). The motion of Love waves is entirely horizontal, or longitudinal. Both are examples of surface waves, or seismic waves whose line of propagation is along the surface of a medium, such as the solid earth. These waves tend to be slower and more destructive than body waves, defined as waves whose line of propagation is through the body of a medium. Body waves include P-waves (primary waves), which are extremely fast moving and longitudinal, and S-waves (secondary waves), which move somewhat less fast and are transverse. The respective



A seismograph reading from the 1989 Loma Prieta, California, earthquake. *(© Russell D. Curtis/Photo Researchers. Reproduced by permission.)*

waves' rates of propagation through the solid earth are as follows:

- P-waves: about 4 mi. (6.4 km) per second
- S-waves: about 2 mi. (3.2 km) per second
- Rayleigh and Love waves: less than 2 mi. per second

REAL-LIFE APPLICATIONS

The Lisbon Quake and Its Effects

On November 1, 1755, the Portuguese capital of Lisbon became the site of one of the worst earthquakes in European history. The event had a number of aftereffects, natural and immediate as well as human and longer term. The results from nature were devastating; the earthquake caused a tsunami, or tidal wave, that flooded the Tagus River even as a fire, also caused by the earthquake, raged through the city.

Estimates of the deaths related directly or indirectly to the Lisbon quake range from 10,000 to as many as 60,000, making it the worst European earthquake since 1531. That earlier quake, incidentally, also had occurred in Lisbon—another example of the fact that certain areas are more prone to seismic activity. It so happens that Portugal lies near the boundary between the Eurasian and African plates.

As for the human response to the quake, it is best represented by the French writer Voltaire (1694–1778). Always a critic of religious faith, Voltaire saw in the incident evidence that called into question Christians' belief in a loving God. He made this case both in the philosophical poem *Le désastre de Lisbonne* (The disaster of Lisbon, 1756) and, more memorably, in the satirical novel *Candide* (1759).

Michell and the birth of seismology. Another, much less famous, thinker responded to the Lisbon earthquake in quite a different fashion. This was English geologist and astronomer John Michell (*ca.* 1724–1793), who studied the event and concluded that quakes are accompanied by shock waves. In an article published in 1760, he noted that earthquakes are found to occur near volcanoes and suggested that they are caused by pressure produced by water that boils from volcanic heat. He also indicated that one can calculate the center of an earthquake by making note of the time at which the motions are felt.

Today Michell is regarded as the father of seismology, a discipline that began to mature in

the nineteenth century. The name itself was coined by the Irish engineer Robert Mallet (1810–1881), who in 1846 compiled the first modern catalogue of earthquakes. Eleven years after publishing the book, which listed all known quakes of any significance since 1606 B.C., Mallet conducted experiments with shock waves by exploding gunpowder and measuring the rate at which the waves travel through various types of material.

Detecting and Measuring Seismic Activity

As noted earlier, seismology is concerned with seismic waves, which generally are caused by movements within the solid earth. These waves also may be produced by man-made sources. Seismologic studies assist miners in knowing how much dynamite to use for a quarry blast so as to be effective without destroying the mine itself or the resources being sought. In addition, seismology can be used to reveal the location of such materials as coal and oil.

Thanks to seismometers (instruments for detecting seismic waves) and seismographs, which record information regarding those waves, seismologists are able to detect not only natural seismic activity but also the effects of underground nuclear testing. Underground testing is banned by international treaty, and if a "rogue nation" were to conduct such testing, it would come to the attention of the World-Wide Standardized Seismograph Network (WWSSN), which consists of 120 seismic stations in some 60 countries.

Most of the remainder of this essay is devoted to a single type of seismic phenomenon: earthquakes. As noted, they are far from the only effect of seismic activity; however, they are the most prevalent and well documented. A close second would be volcanoes, which are discussed in the essay Mountains.

Early seismographic instruments. In A.D. 132, the Chinese scientist Chang Heng (78–139) constructed what may have been the first seismographic instrument, which was designed to detect not only the presence of seismic activity but also the direction from which it came. His invention ultimately was discarded, however, and understanding of earthquakes progressed little for more than 1,600 years.

The first crude seismograph was invented in 1703 by the French physicist Jean de Hautefeuille (1647–1724), long before Michell formally established a connection between shock waves and earthquakes. Historians date the starting point of modern seismographic monitoring, however, to an 1880 invention by the English geologist John Milne (1850–1913). Milne's creation, the first precise seismograph, measured motion with a horizontal pendulum attached to a pen that recorded movement on a revolving drum. Milne used his device to record earthquakes from as far away as Japan and helped establish seismologic stations around the world. The first modern seismograph in the United States was installed at the University of California at Berkeley and proved its accuracy in recording the 1906 San Francisco quake, discussed later in this essay.

Magnitude: the Richter scale. An earthquake can be measured according to either its magnitude or its intensity. The first refers to the amount of energy released by the earthquake, and its best-known scale of measurement is the Richter scale. Developed in 1935 by the American geophysicist Charles Richter (1900–1985), the Richter scale is logarithmic rather than arithmetic, meaning that increases in value involve multiplication rather than addition.

The numbers on the Richter scale, from 1.0 to 10.0, should be thought of as exponents rather than integers. Each whole-number increase represents a tenfold increase in the amplitude (size from crest to trough) of the seismic wave. Therefore 2.0 is not twice as much as 1.0; it is 10 times as much. To go from 1.0 to 3.0 is an increase by a factor of 100, and to go from 1.0 to 4.0 indicates an increase by a factor of 1,000. The scales of magnitude thus become ever greater, and while a whole-number increase on the Richter scale indicates an increase of amplitude by a factor of 10, it represents an increase of energy by a factor of about 31.

Intensity: the Mercalli scale. The amplitude and energy measured by the Richter scale are objective and quantitative, whereas intensity is more subjective and qualitative. Intensity, an indication of the earthquake's effect on human beings and structures, is measured by the Mercalli scale, named after the Italian seismologist Giuseppe Mercalli (1850–1914). The 12 levels on the Mercalli scale range

from I, which means that few people felt the quake, to XII, which indicates total damage. A few comparisons serve to illustrate the scales' relationship to each other.

A score of I on the Mercalli scale equates to a value between 1.0 and a 3.0 on the Richter scale and indicates a tremor felt only by a very few people under very specific circumstances. At 5.0 to 5.9 on the Richter scale (VI to VII on the Mercalli scale), everyone feels the earthquake, and many people are frightened, but only the most poorly built structures are damaged significantly. Above 7.0 on the Richter scale and VIII on the Mercalli scale, wooden and then masonry structures collapse, as do bridges, while railways are bent completely out of shape. In populated areas, as we shall see, the death toll can be enormous.

Famous Quakes

The great San Francisco earthquake, which struck on April 18, 1906, spawned a massive fire, and these events resulted in the deaths of some 700 people, including 270 inmates of a mental institution. Another 300,000 people were left homeless, and 490 city blocks were destroyed. Ultimately, the financial impact of the San Francisco quake proved to be one of the contributing factors in the March 13, 1907, stock market crash that played a key role in the panic of 1907.

At 5:04 P.M. on October 17, 1989, another quake struck San Francisco. It lasted just 15 seconds, long enough to kill some 90 people and cause $6 billion in property damage. Though it was the biggest quake since the 1906 tremor, it was much smaller: 7.19 on the Richter scale, or about one-fifth of the 7.7 measured for the 1906 quake. The 1989 Loma Prieta quake cost much more than the earlier tragedy, which had caused $500 million in damage, but, of course, half a billion dollars in 1906 was worth a great deal more than $6 billion 83 years later.

Neither earthquake, however, was the greatest in American history; in fact, the 1989 quake does not rank among the top 15, even for the continental United States. The eight worst earthquakes in U.S. history all occurred in one state: Alaska. Greatest of all was the March 27, 1964, quake at Prince William Sound, which registered a staggering 9.2 on the Richter scale and took 125 lives. Of that number, 110 were killed in a tsunami resulting from the quake.

The high incidence of earthquakes in Alaska is understandable enough, given the fact that its southern edge abuts a subduction zone and, along with the panhandle, sits astride the boundary between the North American and Pacific plates. Although this may not be much comfort to people in Alaska, it is fortunate that the most earthquake-prone state is also the most sparsely populated. Had the epicenter (the point on Earth's surface directly above the hypocenter, or focal point from which a quake originates) of the 1964 earthquake been in New York City, the death toll would have been closer to 125,000 than 125.

GREATEST QUAKES IN THE CONTINENTAL UNITED STATES. Similarly, it is fortunate that the greatest quakes to strike the continental United States outside California have been in low-population centers. Of the 15 worst earthquakes in U.S. history, only one was outside Alaska, California, or Hawaii. In fact, it was the site of both the worst and the fifth-worst earthquakes in the continental United States: New Madrid, Missouri, site of a 7.9 quake on February 7, 1812, and a 7.7 quake just two months earlier, on December 16, 1811.

New Madrid lies at the extreme southeastern tip of Missouri, near the Mississippi River and within a few hundred miles of several major cities: St. Louis, Missouri; Memphis and Nashville, Tennessee; and Louisville, Kentucky. Had the 1811 and 1812 quakes occurred today, they undoubtedly would have taken a vast human toll owing to the resulting floods. As it was, some lakes rose by as much as 15 ft. (4.6 m), streams changed direction, and the Mississippi and Ohio rivers flowed backward. Fortunately, however, they occurred at a time when the Missouri Territory—it was not even a state yet—and surrounding areas were sparsely populated. The combined death toll was in the single digits.

Of the top 15 earthquakes in the continental United States, all but the 1906 San Francisco quake (which ranks sixth) took place in areas with small populations. Ten were in California but generally in less populous areas or at times when there were fewer people there (e.g., no. 2: Fort Tejon, 1857; no. 3: Owens Valley, 1872; and no. 4: Imperial Valley, 1892). Other than the two New Madrid quakes, the remainder took place in Nevada (no. 12: Dixie Valley, 1954), Montana (no. 13: Hebgen Lake, 1959), and Idaho (no. 14:



Earthquake damage in California. *(© David Weintraub/Photo Researchers. Reproduced by permission.)*

Borah Peak, 1983). As of late 2001, the Idaho quake was the second most recent, after no. 9, at Landers, California, in 1992. (The 1994 Northridge quake, in the Los Angeles area, ranked 6.7 on the Richter scale, well below the 7.3 registered by no. 15, west of Eureka, California, in 1922.)

The world's most destructive quakes. None of these U.S. quakes, however, compares with the July 27, 1976, earthquake in T'ang-shan, China. The worst earthquake in modern history, it shattered some 20 sq. mi. (32 km sq.) near the capital city of Beijing

and killed about 242,000 people while injuring an estimated 600,000 more. There are several interesting aspects to this quake, aside from its sheer scale.

One is sociological, involving the human response to the quake. As in Portugal in 1755, people saw events in a cosmic light; in this case, though, they did not interpret the quake as evidence of divine unconcern but quite the opposite. Mao Tse-tung (1893–1976), by far the most influential Chinese leader of modern times, had just died, and the Chinese saw the natural disaster as fitting into a larger historical pattern. In the traditional Chinese view, earthquakes, floods, and other signs from the gods attend the change of dynasties.

Also interesting is the fact that the T'ang-shan quake was merely the most destructive in a worldwide series of quakes that took place between February and November 1976. In the course of these events, 23,000 people died in Guatemala after a February 4 quake; 3,000 people were reported dead, and 3,000 more were missing in Indonesia, as a result of a series of quakes and landslides on June 26 (later, the U.S. Federal Emergency Management Agency, or FEMA, placed the number of dead from the Indonesia quake at just 443); as many as 8,000 people died in an earthquake and tsunami that hit the southern Philippines on August 16; and 4,000 more perished in a November 24 quake in eastern Turkey.

Similarly, a few months before the 1755 Lisbon earthquake, a quake hit northern Iran. This is an aspect of seismology that cannot be explained readily by plate tectonics: Iran and Portugal are not on the same plate margins; in fact, northern Iran is not on a plate margin at all. Likewise, the areas hit in the 1976 quakes were not on the same plate margins, and T'ang-shan (unlike the other places affected) is not on a major plate margin at all. Nor is Shansi in north-central China, site of history's most destructive earthquake on January 24, 1556, which killed more than 830,000 people.

Note that the 1556 and 1976 Chinese quakes were the worst, respectively, of all history and of modern times—but *worst* in terms of intensity, not magnitude. One might say that they were the most destructive but not the worst in pure terms. The 1976 quake is not even on the list of the 10 worst earthquakes—those of the greatest magnitude—in the twentieth century. Whereas the T'ang-shan quake registered 8.0, a quake in Chile on May 22, 1960, had a magnitude of 9.5, or about 50 times greater, yet the death toll was much smaller—2,000 people killed. Three thousand more were injured in the Chilean quake, and two million were rendered homeless. The last statistic perhaps best signifies the magnitude of the 1960 quake, which caused tsunamis that brought death and destruction as far away as Hawaii, Japan, the Philippines, and the west coast of the United States.

Learning from Seismology

As noted, plate tectonics does not explain every earthquake, but it does explain most, probably about 90%. Not that it is much help in predicting earthquakes, because the processes of plate tectonics take place on an entirely different time scale than the ones to which humans are accustomed. These processes happen over millions of years, so it is hard to say, for any particular year, just what will happen to a particular plate.

Plate tectonics, then, tells us only areas of likelihood for earthquakes—specifically, plate boundaries of the types discussed near the end of Plate Tectonics. And even though the processes that create the conditions for an earthquake are extremely slow, usually the discernible indications that an earthquake is coming appear only seconds before the quake itself. Thus, as sophisticated as modern seismometers are, they generally do not provide enough advance notice of earthquakes to offer any lifesaving value.

There are not just a few earthquakes each year but many thousands of tremors, most of them too small to register. Sometimes these tremors may be foreshocks, or indicators that a quake is coming to a particular area. In addition, studies of other phenomena, from tidal behavior to that of animals (probably a result of some creatures' extremely acute hearing), may offer suggestions as to the locations of future quakes.

EARTH'S CORE AND THE MOHO. Seismology is useful for learning about more than just earthquakes or volcanoes. During the early years of the twentieth century, the Irish geologist Richard Dixon Oldham (1858–1936) studied data from a number of recent earthquakes and noticed a difference in the behavior of compression waves and shear waves. (These terms merely express the differ-

KEY TERMS

AMPLITUDE: The maximum displacement of a vibrating material, or the "size" of a wave from crest to trough.

BODY WAVES: Waves whose line of propagation is through the body of a medium. These include P-waves (primary waves), which move extremely fast and are longitudinal, and S-waves (secondary waves), which are move somewhat less fast and are transverse. Compare with *surface waves.*

COMPRESSION: A form of stress produced by the action of equal and opposite forces, the effect of which is to reduce the length of a material. Compression is a form of pressure.

CONTINENTAL DRIFT: The theory that the configuration of Earth's continents was once different than it is today, that some of the individual landmasses of today once were joined in other continental forms, and that these landmasses later separated and moved to their present locations.

CONVERGENCE: A tectonic process whereby plates move toward each other. Usually associated with subduction, convergence typically occurs in the ocean, creating an oceanic trench. It is one of the three ways, along with divergence and transform motion, that plates interact.

CORE: The center of Earth, an area constituting about 16% of the planet's volume and 32% of its mass. Made primarily of iron and another, lighter element (possibly sulfur), it is divided between a solid inner core with a radius of about 760 mi. (1,220 km) and a liquid outer core about 1,750 mi. (2,820 km) thick.

CRUST: The uppermost division of the solid earth, representing less than 1% of its volume and varying in depth from 3–37 mi. (5–60 km). Below the crust is the mantle.

DIVERGENCE: A tectonic process whereby plates move away from each other. Divergence results in the separation of plates and most often is associated either with seafloor spreading or the formation of rift valleys. It is one of the three ways, along with convergence and transform motion, that plates interact.

ELASTICITY: The response of solids to stress.

EPICENTER: The point on Earth's surface directly above the hypocenter, or the focal point from which an earthquake originates.

FAULT: An area of fracturing, as a result of stress, between rocks.

FOLD: An area of rock that has been bent by stress.

GEOPHYSICS: A branch of the earth sciences that combines aspects of geology and physics. Geophysics addresses the planet's physical processes as well as its gravitational, magnetic, and electric properties and the means by which energy is transmitted through its interior.

HEAT: Internal thermal energy that flows from one body of matter to another.

HOT SPOT: A region of high volcanic activity.

KEY TERMS CONTINUED

INTENSITY: Where earthquakes are concerned, intensity refers to the amount of damage to humans and buildings. Subjective and qualitative (as opposed to magnitude, which is objective and quantitative), intensity is measured by the Mercalli scale.

KINETIC ENERGY: The energy that an object possesses by virtue of its motion.

LITHOSPHERE: The upper layer of Earth's interior, including the crust and the brittle portion at the top of the mantle.

LONGITUDINAL WAVE: A wave in which the movement of vibration is in the same direction as the wave itself. This is contrasted with a *transverse wave.*

LOVE WAVES: See *surface waves.*

MAGNITUDE: Where earthquakes are concerned, magnitude refers to the amount of energy released by the quake as well as the amplitude of the seismic waves. Objective and quantitative (as opposed to intensity, which is subjective and qualitative), magnitude is measured by the Richter scale.

MANTLE: The thick, dense layer of rock, approximately 1,429 mi. (2,300 km) thick, between Earth's crust and its core. In reference to the other terrestrial planets, *mantle* simply means the area of dense rock between the crust and core.

MERCALLI SCALE: See *intensity.*

PLATE MARGINS: Boundaries between plates.

PLATE TECTONICS: The name both of a theory and of a specialization of tectonics. As an area of study, plate tectonics deals with the large features of the lithosphere and the forces that shape them. As a theory, it explains the processes that have shaped Earth in terms of plates and their movement. Plate tectonics theory brings together aspects of continental drift, seafloor spreading, seismic and volcanic activity, and the structures of Earth's crust to provide a unifying model of Earth's evolution. It is one of the dominant concepts in the modern earth sciences.

PLATES: Large, movable segments of the lithosphere.

PROPAGATION: The act or state of traveling from one place to another.

P-WAVES: See *body waves.*

RADIOACTIVITY: A term describing a phenomenon whereby certain materials are subject to a form of decay brought about by the emission of high-energy particles or radiation. Forms of particles or energy include alpha particles (positively charged helium nuclei); beta particles (either electrons or subatomic particles called *positrons*); or gamma rays, which occupy the highest energy level in the electromagnetic spectrum.

RAYLEIGH WAVES: See *surface waves.*

RICHTER SCALE: See *magnitude.*

SEISMIC WAVE: A packet of energy resulting from the disturbance that accompanies a strain on rocks in the lithosphere.

SEISMOGRAPH: An instrument designed to record information regarding seismic waves.

KEY TERMS CONTINUED

SEISMOLOGY: The study of seismic waves as well as the movements and vibrations that produce them.

SEISMOMETER: An instrument for detecting seismic waves.

SHEAR: A form of stress resulting from equal and opposite forces that do not act along the same line. If a thick, hardbound book is lying flat and one pushes the front cover from the side so that the covers and pages no longer constitute parallel planes, this is an example of shear.

STRAIN: The ratio between the change in dimension experienced by an object that has been subjected to stress and the original dimensions of the object.

STRESS: In general terms, any attempt to deform a solid. Types of stress include tension, compression, and shear.

SUBDUCTION: A tectonic process that results when plates converge, and one plate forces the other down into Earth's mantle. As a result, the subducted plate eventually undergoes partial melting.

SURFACE WAVES: Seismic waves whose line of propagation is along the surface of a medium such as the solid earth. These waves tend to be slower and more destructive than body waves. Examples include Rayleigh waves (waves with both transverse and longitudinal characteristics) and Love waves (purely longitudinal). Compare with *body waves.*

S-WAVES: See *body waves.*

TECTONICS: The study of tectonism, including its causes and effects, most notably mountain building.

TECTONISM: The deformation of the lithosphere.

TENSION: A form of stress produced by a force that acts to stretch a material.

THERMAL ENERGY: Heat energy, a form of kinetic energy produced by the motion of atomic or molecular particles in relation to one another. The greater the relative motion of these particles, the greater the thermal energy.

TRANSFORM MOTION: A tectonic process whereby plates slide past each other. It is one of the three ways, along with convergence and divergence, that plates interact.

TRANSVERSE WAVE: A wave in which the vibration or motion is perpendicular to the direction in which the wave is moving. Compare with *longitudinal wave.*

TSUNAMI: A tidal wave produced by an earthquake or volcanic eruption. The term comes from the Japanese words for "harbor" and "wave."

ences in stress produced by seismic waves.) As it turns out, shear waves are deflected as they pass through the center of Earth. Since liquid cannot experience shear, this finding told him that the planet's core must be made of molten material.

Oldham's findings, published in 1906—the same year as the great San Francisco quake—made him a pioneer in the application of seismology to the study of Earth's interior. Three years later, studies of earthquake waves by the Croatian geologist Andrija Mohorovicic (1857–1936) revealed still more about the interior of the planet. Based on his analysis of wave speeds and arrival times, Mohorovicic was able to calculate the depth at which the crust becomes the mantle. This change is abrupt rather than gradual, and

the boundary on which it occurs is today known as the Mohorovicic discontinuity, or simply the Moho.

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GEOMORPHOLOGY

GEOMORPHOLOGY
MOUNTAINS
EROSION
MASS WASTING

GEOMORPHOLOGY

CONCEPT

The surface of Earth is covered with various landforms, a number of which are discussed in various entries throughout this book. This essay is devoted to the study of landforms themselves, a subdiscipline of the geologic sciences known as geomorphology. The latter, as it has evolved since the end of the nineteenth century, has become an interdisciplinary study that draws on areas as diverse as plate tectonics, ecology, and meteorology. Geomorphology is concerned with the shaping of landforms, through such processes as subsidence and uplift, and with the classification and study of such landforms as mountains, volcanoes, and islands.

HOW IT WORKS

An Evolving Area of Study

Geomorphology is an area of geology concerned with the study of landforms, with the forces and processes that have shaped them, and with the description and classification of various physical features on Earth. The term, which comes from the Greek words *geo,* or "Earth," and *morph,* meaning "form," was coined in 1893 by the American geologist William Morris Davis (1850–1934), who is considered the father of geomorphology.

During Davis's time, geomorphology was concerned primarily with classifying different structures on Earth's surface, examples of which include mountains and islands, discussed later in this essay. This view of geomorphology as an essentially descriptive, past-oriented area of study closely aligned with historical geology prevailed throughout the late nineteenth and early twentieth centuries.

By the mid-twentieth century, however, the concept of geomorphology inherited from Davis had fallen into disfavor, to be replaced by a paradigm, or model, oriented toward physical rather than historical geology. (These two principal branches of geology are concerned, in the first instance, with Earth's past and the processes that shaped it and, in the second instance, with Earth's current physical features and the processes that continue to shape it.)

RETHINKING GEOMORPHOLOGY. As reconceived in the 1950s and thereafter, geomorphology became an increasingly exact science. As has been typical of many sciences in their infancy, early geomorphology focused on description rather than prediction and tended to approach its subject matter in a qualitative fashion. The term qualitative suggests a comparison between qualities that are not defined precisely, such as "fast" and "slow" or "warm" and "cold." On the other hand, a quantitative approach, as has been implemented for geomorphology from the mid–twentieth century onward, centers on a comparison between precise quantities—for instance, 10 lb. (4.5 kg) versus 100 lb. (45 kg) or 50 MPH (80.5 km/h) versus 120 MPH (193 km/h).

As part of its shift in focus, geomorphology began to treat Earth's physical features as systems made up of complex and ongoing interactions. This view fell into line with a general emphasis on the systems concept in the study of Earth. (See Earth Systems for more about the systems concept.) As geomorphology evolved, it became more interdisciplinary, as we shall see. This, too,



Mount Machhapuchhare in the Himalayas. The Himalayas were formed through the process of uplift, or rising of Earth's surface. *(© George Turner/Photo Researchers. Reproduced by permission.)*

was part of an overall trend in the earth sciences toward an approach that viewed subjects in broad, cross-disciplinary terms as opposed to a narrow focus on specific areas of study.

Landforms and Processes

Two concerns are foremost within the realm of geomorphology, and these concerns reflect the stages of its history. First, in line with Davis's original conception of geomorphology as an area of science devoted to classifying and describing natural features, there is its concern with topography. The latter may be defined as the configuration of Earth's surface, including its relief (elevation and other inequalities) as well as the position of physical features.

These physical features are called landforms, examples of which include mountains, plateaus, and valleys. Geomorphology always has involved classification, and early scientists working in this subdiscipline addressed the classification of landforms. Other systems of classification, however, are not so concerned with cataloging topographical features themselves as with differentiating the processes that shaped them. This brings us to the other area of interest in geomorphology: the study of how landforms came into being.

Shaping the Earth. Among the processes that drive the shaping of landforms is plate tectonics, or the shifting of large, movable segments of lithosphere (the crust and upper layer of Earth's mantle). Plate tectonics is dis-

cussed in detail within its own essay and more briefly in other areas throughout this book, as befits its status as one of the key areas of study in the earth sciences.

Other processes also shape landforms. Included among these processes are weathering, the breakdown of rocks and minerals at or near the surface of Earth due to physical or chemical processes; erosion, the movement of soil and rock due to forces produced by water, wind, glaciers, gravity, and other influences; and mass wasting or mass movement, the transfer of earth material, by processes that include flow, slide, fall, and creep, down slopes. Also of interest are fluvial and eolian processes (those that result from water flow and wind, respectively) as well as others related to glaciers and coastal formations.

Human activity also can play a significant role in shaping Earth. This effect may be direct, as when the construction of cities, the building of dams, or the excavation of mines alters the landscape. On the other hand, it can be indirect. In the latter instance, human activity in the biosphere exerts an impact, as when the clearing of forest land or the misuse of crop land results in the formation of a dust bowl.

Interdisciplinary Studies

As noted earlier, geomorphology is characteristic of the earth sciences as a whole in its emphasis on an interdisciplinary approach. As is true of earth scientists in general, those studying landforms and the processes that shape them do not work simply in one specialty. Among the areas of interest in geomorphology are, for example, deep-sea geomorphology, which draws on oceanography, and planetary geomorphology, the study of landscapes on other planets.

When studying coastal geomorphology, a geologist may draw on realms as diverse as fluid mechanics (an area of physics that studies the behavior of gases and liquids at rest and in motion) and sedimentology. The investigation of such processes as erosion and mass wasting calls on knowledge in the atmospheric sciences as well as the physics and chemistry of soil. It is almost inevitable that a geomorphologic researcher will draw on geophysics as well as on such subspecialties as volcanology. These studies may go beyond the "hard sciences," bringing in such social sciences as geography.

REAL-LIFE APPLICATIONS

Subsidence

Subsidence refers to the process of subsiding (settling or descending), on the part of either an air column or the solid earth, or, in the case of solid earth, to the resulting formation or depression. Subsidence in the atmosphere is discussed briefly in the entry Convection. Subsidence that occurs in the solid earth, known as geologic subsidence, is the settling or sinking by a body of rock or sediment. (The latter can be defined as material deposited at or near Earth's surface from a number of sources, most notably preexisting rock.)

As noted earlier, many geomorphologic processes can be caused either by nature or by human beings. An example of natural subsidence takes place in the aftermath of an earthquake, during which large areas of solid earth may simply drop by several feet. Another example can be observed at the top of a volcano some time after it has erupted, when it has expelled much of its material (i.e., magma) and, as a result, has collapsed.

Natural subsidence also may result from cave formation in places where underground water has worn away limestone. If the water erodes too much limestone, the ceiling of the cave will subside, usually forming a sinkhole at the surface. The sinkhole may fill with water, making a lake; the formation of such sinkholes in many spots throughout an area (whether the sinkholes become lakes or not), is known as karst topography.

In places where the bedrock is limestone—particularly in the sedimentary basins of rivers—karst topography is likely to develop. The United States contains the most extensive karst region in the world, including the Mammoth cave system in Kentucky. Karst topography is very pronounced in the hills of southern China, and karst landscapes have been a prominent feature of Chinese art for centuries. Other extensive karst regions can be found in southern France, Central America, Turkey, Ireland, and England.

MAN-MADE SUBSIDENCE. Man-made subsidence often ensues from the removal of groundwater or fossil fuels, such as petroleum or coal. Groundwater removal can be perfectly safe, assuming the area experiences sufficient

rainfall to replace, or recharge, the lost water. If recharging does not occur in the necessary proportions, however, the result will be the eventual collapse of the aquifer, a layer of rock that holds groundwater.

In so-called room-and-pillar coal mining, pillars, or vertical columns, of coal are left standing, while the areas around them are extracted. This method maintains the ceiling of the "room" that has been mined of its coal. After the mine is abandoned, however, the pillar eventually may experience so much stress that it breaks, leading to the collapse of the mined room. As when the ceiling of a cave collapses, the subsidence of a coal mine leaves a visible depression above ground.

UPLIFT

As its name implies, uplift describes a process and results opposite to those of subsidence. In uplift the surface of Earth rises, owing either to a decrease in downward force or to an increase in upward force. One of the most prominent examples of uplift is seen when plates collide, as when India careened into the southern edge of the Eurasian landmass some 55 million years ago. The result has been a string of mountain ranges, including the Himalayas, Karakoram Range, and Hindu Kush, that contain most of the world's tallest peaks.

Plates move at exceedingly slow speeds, but their mass is enormous. This means that their inertia (the tendency of a moving object to keep moving unless acted upon by an outside force) is likewise gargantuan in scale. Therefore, when plates collide, though they are moving at a rate equal to only a few inches a year, they will keep pushing into each other like two automobiles crumpling in a head-on collision. Whereas a car crash is over in a matter of seconds, however, the crumpling of continental masses takes place over hundreds of thousands of years.

When sea floor collides with sea floor, one of the plates likely will be pushed under by the other one, and, likewise, when sea floor collides with continental crust, the latter will push the sea floor under. (See Plate Tectonics for more about oceanic-oceanic and continental-oceanic collisions.) This results in the formation of volcanic mountains, such as the Andes of South America or the Cascades of the Pacific Northwest, or volcanic islands, such as those of Japan, Indonesia, or Alaska's Aleutian chain.

ISOSTATIC COMPENSATION. In many other instances, collision, compression, and extension cause uplift. On the other hand, as noted, uplift may result from the removal of a weight. This occurs at the end of an ice age, when glaciers as thick as 1.9 mi. (3 km) melt, gradually removing a vast weight pressing down on the surface below.

This movement leads to what is called isostatic compensation, or isostatic rebound, as the crust pushes upward like a seat cushion rising after a person is longer sitting on it. Scandinavia is still experiencing uplift at a rate of about 0.5 in. (1 cm) per year as the after-effect of glacial melting from the last ice age. The latter ended some 10,000 years ago, but in geologic terms this is equivalent to a few minutes' time on the human scale.

ISLANDS

Geomorphology, as noted earlier, is concerned with landforms, such as mountains and volcanoes as well as larger ones, including islands and even continents. Islands present a particularly interesting area of geomorphologic study. In general, islands have certain specific characteristics in terms of their land structure and can be analyzed from the standpoint of the geosphere, but particular islands also have unique ecosystems, requiring an interdisciplinary study that draws on botany, zoology, and other subjects.

In addition, there is something about an island that has always appealed to the human imagination, as evidenced by the many myths, legends, and stories about islands. Some examples include Homer's *Odyssey,* in which the hero Odysseus visits various islands in his long wanderings; Thomas More's *Utopia,* describing an idealized island republic; *Robinson Crusoe,* by Daniel Defoe, in which the eponymous hero lives for many years on an island with no companion but the trusty native Friday; *Treasure Island,* by Robert Louis Stevenson, in which the island is the focus of a treasure hunt; and Mark Twain's *Adventures of Huckleberry Finn,* depicting Jackson Island in the Mississippi River, to which Huckleberry Finn flees to escape "civilization."

One of the favorite subjects of cartoonists is that of a castaway stranded on a desert island, a mound of sand with no more than a single tree.

Movies, too, have long portrayed scenarios, from the idyllic to the brutal, that take place on islands, particularly deserted ones, a notable example being *Cast Away* (2000). A famous line by the English poet John Donne (1572–1631) warns that "no man is an island," implying that many wish they could enjoy the independence suggested by the concept of an island. Within the Earth system, however, nothing is fully independent, and, as we shall see, this is certainly the case where islands are concerned.

THE ISLANDS OF EARTH. Earth has literally tens of thousands of islands. Just two archipelagos (island chains), those that make up the Philippines and Indonesia, include thousands of islands each. While there are just a few dozen notable islands on Earth, many more dot the planet's seas and oceans. The largest are these:

- Greenland (Danish, northern Atlantic): 839,999 sq. mi.(2,175,597 sq km)
- New Guinea (divided between Indonesia and Papua New Guinea, western Pacific): 316,615 sq. mi. (820,033 sq km)
- Borneo (divided between Indonesia and Malaysia, western Pacific): 286,914 sq. mi. (743,107 sq km)
- Madagascar (Malagasy Republic, western Indian Ocean): 226,657 sq. mi. (587,042 sq km)
- Baffin (Canadian, northern Atlantic): 183,810 sq. mi. (476,068 sq km)
- Sumatra (Indonesian, northeastern Indian Ocean): 182,859 sq. mi. (473,605 sq km)

The list could go on and on, but it stops at Sumatra because the next-largest island, Honshu (part of Japan), is less than half as large, at 88,925 sq. mi. (230,316 sq km). Clearly, not all islands are created equal, and though some are heavily populated or enjoy the status of independent nations (e.g., Great Britain at number eight or Cuba at number 15), they are not necessarily the largest. On the other hand, some of the largest are among the most sparsely populated.

Of the 32 largest islands in the world, more than a third are in the icy northern Atlantic and Arctic, with populations that are small or practically nonexistent. Greenland's population, for instance, was just over 59,000 in 1998, while that of Baffin Island was about 13,200. On both islands, then, each person has about 14 frozen sq. mi. (22 sq km) to himself or herself, making them among the most sparsely populated places on Earth.



A TINY ISLAND IN THE TRUK LAGOON, MICRONESIA. *(© Stuart Westmorland/Photo Researchers. Reproduced by permission.)*

CONTINENTS, OCEANS, AND ISLANDS. Australia, of course, is not an island but a continent, a difference that is not related directly to size. If Australia *were* an island, it would be by far the largest. Australia is regarded as a continent, however, because it is one of the principal landmasses of the Indo-Australian plate, which is among a handful of major continental plates on Earth. Whereas continents are more or less permanent (though they have experienced considerable rearrangement over the eons), islands come and go, seldom lasting more than 10 million years. Erosion or rising sea levels remove islands, while volcanic explosions can create new ones, as when an eruption off the coast of Iceland resulted in the formation of an island, Surtsey, in 1963.

Islands are of two types, continental and oceanic. Continental islands are part of continental shelves (the submerged, sloping ledges of continents) and may be formed in one of two ways. Rising ocean waters either cover a coastal region, leaving only the tallest mountains exposed as islands or cut off part of a peninsula,

KEY TERMS

BIOSPHERE: A combination of all living things on Earth—plants, animals, birds, marine life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

CONVERGENCE: A tectonic process whereby plates move toward each other. Usually associated with subduction, convergence typically occurs in the ocean, creating an oceanic trench. It is one of the three ways, along with divergence and transform motion, in which plates interact.

CRUST: The uppermost division of the solid earth, representing less than 1% of its volume and varying in depth from 3 to 37 mi. (5 to 60 km). Below the crust is the mantle.

EROSION: The movement of soil and rock due to forces produced by water, wind, glaciers, gravity, and other influences.

GEOLOGY: The study of the solid earth, in particular its rocks, minerals, fossils, and land formations.

GEOMORPHOLOGY: An area of geology concerned with the study of landforms, with the forces and processes that have shaped them, and with the description and classification of various physical features on Earth.

GEOPHYSICS: A branch of the earth sciences that combines aspects of geology and physics. Geophysics addresses the planet's physical processes as well as its gravitational, magnetic, and electric properties and the means by which energy is transmitted through its interior.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

HISTORICAL GEOLOGY: The study of Earth's physical history. Historical geology is one of two principal branches of geology, the other being physical geology.

LANDFORM: A notable topographical feature, such as a mountain, plateau, or valley.

LITHOSPHERE: The upper layer of Earth's interior, including the crust and the brittle portion at the top of the mantle.

MASS WASTING: The transfer of earth material, by processes that include flow, slide, fall, and creep, down slopes. Also known as mass movement.

which then becomes an island. Most of Earth's significant islands are continental and are easily spotted as such, because they lie at close proximity to continental landmasses. Many other continental islands are very small, however; examples include the barrier islands that line the East Coast of the United States. Formed from mainland sand brought to the coast by rivers, these are technically not continental islands, but they more clearly fit into that category than into the grouping of oceanic islands.

Oceanic islands, of which the Hawaiian-Emperor island chain and the Aleutians off the Alaskan coast are examples, form as a result of volcanic activity on the ocean floor. In most cases, there is a region of high volcanic activity,

KEY TERMS CONTINUED

PHYSICAL GEOLOGY: The study of the material components of Earth and of the forces that have shaped the planet. Physical geology is one of two principal branches of geology, the other being historical geology.

PLATE TECTONICS: The name both of a theory and of a specialization of tectonics. As an area of study, plate tectonics deals with the large features of the lithosphere and the forces that shape them. As a theory, it explains the processes that have shaped Earth in terms of plates and their movement.

PLATES: Large, movable segments of the lithosphere.

QUALITATIVE: Involving a comparison between qualities that are not defined precisely, such as "fast" and "slow" or "warm" and "cold."

QUANTITATIVE: Involving a comparison between precise quantities—for instance, 10 lb. versus 100 lb. or 50 mi. per hour versus 120 mi. per hour.

RELIEF: Elevation and other inequalities on a land surface.

SEDIMENT: Material deposited at or near Earth's surface from a number of sources, most notably preexisting rock.

SEDIMENTOLOGY: The study and interpretation of sediments, including sedimentary processes and formations.

SUBSIDENCE: A term that refers either to the process of subsiding (settling or descending), on the part of either air or solid earth or, in the case of solid earth, to the resulting formation. Subsidence thus is defined variously as the downward movement of air, the sinking of ground, or a depression in Earth's crust.

SYSTEM: Any set of interactions that can be set apart mentally from the rest of the universe for the purposes of study, observation, and measurement.

TECTONICS: The study of tectonism, including its causes and effects, most notably mountain building.

TECTONISM: The deformation of the lithosphere.

TOPOGRAPHY: The configuration of Earth's surface, including its relief, as well as the position of physical features.

UPLIFT: A process whereby the surface of Earth rises, due to either a decrease in downward force or an increase in upward force.

WEATHERING: The breakdown of rocks and minerals at or near the surface of Earth due to physical or chemical processes.

called a hot spot, beneath the plates, which move across the hot spot. This is the situation in Hawaii, and it explains why the volcanoes on the southern islands are still active while those to the north are not: the islands themselves are moving north across the hot spot. If two plates converge and one subducts (see Plate Tectonics for an explanation of this process), a deep trench with a parallel chain of volcanic islands may develop. Exemplified by the Aleutians, these chains are called island arcs.

ISLAND ECOSYSTEMS. The ecosystem, or community of all living organisms, on islands can be unique owing to their separation from continents. The number of life-forms on an island is relatively small and can encompass some

unusual circumstances compared with the larger ecosystems of continents. Ireland, for instance, has no native snakes, a fact "explained" by the legend that Saint Patrick drove them away. Hawaii and Iceland are also blessedly free of serpents.

Oceanic islands, of course, tend to have more unique ecosystems than do continental islands. The number of land-based animal lifeforms is necessarily small, whereas the varieties of birds, flying insects, and surrounding marine life will be greater owing to those creatures' mobility across water. Vegetation is relatively varied, given the fact that winds, water currents, and birds may carry seeds.

Nonetheless, ecosystems of islands tend to be fairly delicate and can be upset by the human introduction of new predators (e.g., dogs) or new creatures to consume plant life (e.g., sheep). These changes sometimes can have disastrous effects on the overall balance of life on islands. Overgrazing may even open up the possibility of erosion, which has the potential of bringing an end to an island's life.

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MOUNTAINS

CONCEPT

Among the most striking of geologic features are mountains, created by several types of tectonic forces, including collisions between continental masses. Mountains have long had an impact on the human psyche, for instance by virtue of their association with the divine in the Greek myths, the Bible, and other religious or cultural traditions. One does not need to be a geologist to know what a mountain is; indeed there is no precise definition of mountain, though in most cases the distinction between a mountain and a hill is fairly obvious. On the other hand, the defining characteristics of a volcano are more apparent. Created by violent tectonic forces, a volcano usually is considered a mountain, and almost certainly is one after it erupts, pouring out molten rock and other substances from deep in the earth.

HOW IT WORKS

Plate Tectonics

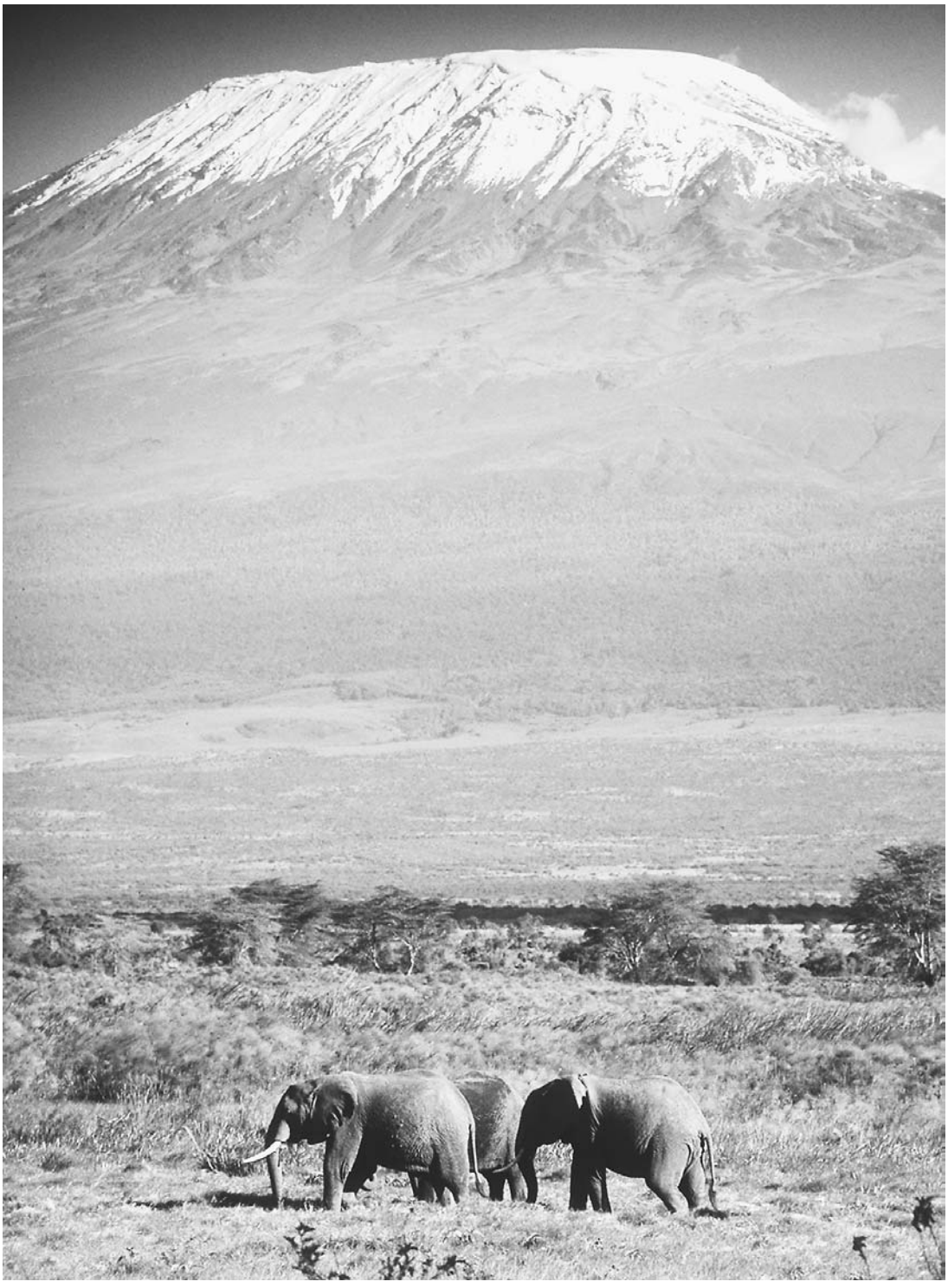
Earth is constantly moving, driven by forces beneath its surface. The interior of Earth itself is divided into three major sections: the crust, mantle, and core. The lithosphere is the upper layer of Earth's interior, including the crust and the brittle portion at the top of the mantle. Tectonism is the deformation of the lithosphere, and the term tectonics refers to the study of this deformation. Most notable among examples of tectonic deformation is mountain building, or orogenesis, discussed later in this essay.

The planet's crust is not all of one piece: it is composed of numerous plates, which are steadily moving in relation to one another. This movement is responsible for all manner of phenomena, including earthquakes, volcanoes, and mountain building. All these ideas and many more are encompassed in the concept of plate tectonics, which is the name for a branch of geologic and geophysical study and of a dominant principle often described as "the unifying theory of geology" (see Plate Tectonics).

CONTENTS UNDER PRESSURE. Tectonism results from the release and redistribution of energy from Earth's interior. This energy is either gravitational, and thus a function of the enormous mass at the planet's core, or thermal, resulting from the heat generated by radioactive decay. Differences in mass and heat within the planet's interior, known as pressure gradients, result in the deformation of rocks, placing many forms of stress and strain on them.

In scientific terms, *stress* is any attempt to deform an object, and strain is a change in dimension resulting from stress. Rocks experience stress in the form of tension, compression, and shear. Tension acts to stretch a material, whereas compression is a form of stress produced by the action of equal and opposite forces, whose effect is to reduce the length of a material. (Compression is a form of pressure.) Shear results from equal and opposite forces that do not act along the same plane. If a thick, hardbound book is lying flat, and one pushes the front cover from the side so that the covers and pages are no longer in alignment, is an example of shear.

Rocks manifest the strain resulting from these stresses by warping, sliding, or breaking. They may even flow, as though they were liquids, or melt and thus truly become liquid. As a result, Earth's interior may manifest faults, or fractures in rocks, as



Mountains sometimes arise in isolation, as was the case with Mount Kilimanjaro in Tanzania. *(© T. Davis/Photo Researchers. Reproduced by permission.)*

well as folds, or bends in the rock structure. The effects can be seen on the surface in the form of subsidence, which is a depression in the crust; or uplift, the raising of crustal materials. Earthquakes and volcanic eruptions also may result.

Orogenesis

There are two basic types of tectonism: epeirogenesis and orogenesis. The first takes its name from the Greek words *epeiros,* meaning "main-

land," and *genesis,* or "origin." Epeirogenesis, which takes the form of either uplift or subsidence, is a chiefly vertical form of movement and plays little role in either plate tectonics or mountain building.

Orogenesis, on the other hand, *is* mountain building, as the prefix *oros* ("mountain") shows. Orogenesis involves the formation of mountain ranges by means of folding, faulting, and volcanic activity—lateral movements as opposed to vertical ones. Geologists typically use the term *orogenesis,* instead of just "mountain building," when discussing the formation of large belts of mountains from tectonic processes.

PLATE MARGINS. Plates may converge (move toward one another), diverge (move away from one another), or experience transform motion, meaning that they slide against one another. Convergence usually is associated with subduction, in which one plate is forced down into the mantle and eventually undergoes partial melting. This typically occurs in the ocean, creating a depression known as an oceanic trench.

There are three types of plate margins, or boundaries between plates, depending on the two types of crusts that interact: oceanic with oceanic, continental with continental, or continental with oceanic. Any of these margins may be involved in mountain formation. Orogenic belts, or mountain belts, typically are situated in subduction zones at convergent plate boundaries and consist of two types.

The first type occurs when igneous material (i.e., rock from volcanoes) forms on the upper plate of a subduction zone, causing the surface to rise. This can take place either in the oceanic crust, in which case the mountains formed are called island arcs, or along continental-oceanic margins. The Aleutian Islands are an example of an island arc, while the Andes range represent mountains formed by the subduction of an oceanic plate under a continental one.

The second type of mountain belt occurs when continental plates converge or collide. When continental plates converge, one plate may "try" to subduct the other, but ultimately the buoyancy of the lower plate (which floats, as it were, on the lithosphere) pushes it upward. The result is the creation of a wide, unusually thick or "tall" belt. An example is the Himalayas, the world's tallest mountain range, which is still being pushed upward as the result of a collision between India and Asia that happened some 30 million years ago. (See Plate Tectonics for more about continental drift and collisions between plates.)

REAL-LIFE APPLICATIONS

What Is a Mountain?

In the 1995 film *The Englishman Who Went Up a Hill But Came Down a Mountain,* the British actor Hugh Grant plays an English cartographer, or mapmaker, sent in 1917 by his government to measure what is purportedly "the first mountain inside Wales." He quickly determines that according to standards approved by His Majesty, the "mountain" in question is, in fact, a hill. Much of the film's plot thereafter revolves around attempts on the part of the villagers to rescue their beloved mountain from denigration as a "hill," a fate they prevent by piling enough rocks and dirt onto the top to make it meet specifications.

This comedy aptly illustrates the somewhat arbitrary standards by which people define mountains. The British naturalist Roderick Peattie (1891–1955), in his 1936 book *Mountain Geography,* maintained that mountains are distinguished by their impressive appearance, their individuality, and their impact on the human imagination. This sort of qualitative definition, while it is certainly intriguing, is of little value to science; fortunately, however, more quantitative standards exist.

In Britain and the United States, a mountain typically is defined as a landform with an elevation of 985 ft. (300 m) above sea level. This was the standard applied in *The Englishman,* but the Welsh villagers would have had a hard time raising their "hill" to meet the standards used in continental Europe: 2,950 ft. (900 m) above sea level. This seems to be a more useful standard, because the British and American one would take in high plains and other nonmountainous regions of relatively great altitude. On the other hand, there are landforms in Scotland that rise only a few hundred meters above sea level, but their morphologic characteristics or shape seem to qualify them as mountains. Not only are their slopes steep, but the presence of glaciers and snow-capped peaks, with their attendant severe weath-

er and rocky, inhospitable soil, also seem to indicate the topography associated with mountains.

Mountain Geomorphology

One area of the geologic sciences especially concerned with the study of mountains is geomorphology, devoted to the investigation of landforms. Geomorphologists studying mountains must draw on a wide variety of disciplines, including geology, climatology, biology, hydrology, and even anthropology, because, as discussed at the conclusion of this essay, mountains have played a significant role in the shaping of human social groups.

From the standpoint of geology and plate tectonics, mountain geomorphology embraces a complex of characteristic formations, not all of which are necessarily present in a given orogen, or mountain. These include forelands and foredeeps along the plains; foreland fold-and-thrust belts, which more or less correspond to "foothills" in layperson's terminology; and a crystalline core zone, composed of several types of rock, that is the mountain itself.

Environmental zones. Mountain geomorphology classifies various environmental zones, from lowest to highest altitude. Near the bottom are flood plains, river terraces, and alluvial fans, all areas heavily affected by rivers flowing from higher elevations. (In fact, many of the world's greatest rivers flow from mountains, examples being the Himalayan Ganges and Indus rivers in Asia and the Andean Amazon in South America.) Farming villages may be found as high as the 9,845-ft. to 13,125-ft. range (3,000–4,000 m), an area known as a submontane, or forested region.

The tree line typically lies at an altitude of 14,765 ft. (4,500 m). Above this point, there is little human activity but plenty of geologic activity, including rock slides, glacial flow, and, at very high altitudes, avalanches. From the tree line upward, the altitude levels that mark a particular region are differentiated for the Arctic and tropical zones, with much lower altitudes in the Arctic mountains. For instance, the tree line lies at about 330 ft. (100 m) in the much colder Arctic zone.

Above the tree line is the subalpine, or montane, region. The mean slope angle of the mountain is less steep here than it is at lower or higher elevations: in the submontane, or forested region, below the tree line, the slope is about 30°, and above the subalpine, in the high alpine, the slope can become as sharp at 65°. In the subalpine, however, it is only about 20°, and because grass (if not trees) grows in this region, it is suited for grazing.

It may seem surprising to hear of shepherds bringing sheep to graze at altitudes of 16,400 ft. (5,000 m), as occurs in tropical zones. This does not necessarily mean that people live at such altitudes; more often than not, mountain dwellers have their settlements at lower elevations, and shepherds simply take their flocks up into the heights for grazing. Yet the ancient Bolivian city of Tiahuanaco, which flourished in about A.D. 600—some four centuries before the rise of the Inca—lay at an almost inconceivable altitude of 13,125 ft. (4,000 m), or about 2.5 times the elevation of Denver, Colorado, America's Mile-High City.

Classifying Mountains

There are several ways to classify mountains and groups of mountains. Mountain belts, as described earlier, typically are grouped according to formation process and types of plates: island arcs, continental arcs (formed with the subduction of an oceanic plate by a continental plate), and collisional mountain belts. Sometimes a mountain arises in isolation, an example being Kilimanjaro in Tanzania, Africa. Another example is Stone Mountain outside Atlanta, an exposed pluton, or a mass of crystalline igneous rock that forms deep in Earth's crust and rises. Many volcanoes, which we discuss later, arise individually, but mountains are most likely to appear in conjunction with other mountains. One such grouping, though far from the only one, is a mountain range, which can be defined as a relatively localized series of peaks and ridges.

Ranges, chains, and masses. Some of the world's most famous mountain ranges include the Himalayas, Karakoram Range, and Pamirs in central Asia; the Alps and Urals in Europe; the Atlas Mountains in Africa; the Andes in South America; and the Cascade Range, Sierra Nevada, Rocky Mountains, and Appalachians as well as their associated ranges in North America. Ranges affiliated with the Appalachians, for instance, include the Great Smokies in the south and the Adirondacks, Alleghenies, and Poconos in the north.

Several of the examples given here illustrate the fact that ranges are not the largest groupings of mountains. Sometimes series of ranges stretch across a continent for great distances in what are called mountain chains, an example of which is the Mediterranean chain of Balkans, Apennines, and Pyrenees that stretches across southern Europe.

There also may be irregular groupings of mountains, which lack the broad linear sweep of mountain ranges or chains and which are known as mountain masses. The mountains surrounding the Tibetan plateau represent an example of a mountain mass. Finally, ranges, chains, and masses of mountains may be combined to form vast mountain systems. An impressive example is the Alpine-Himalayan system, which unites parts of the Eurasian, Arabian, African, and Indo-Australian continental plates.

OTHER TYPES OF MOUNTAIN. There are certain special types of orogeny, as when ocean crust subducts continental crust—something that is not supposed to happen but occasionally does. This rare variety of subduction is called obduction, and the mountains produced are called ophiolites. Examples include the uplands near Troodos in Cyprus and the Taconic Mountains in upstate New York.

Fault-block mountains appear when two continental masses push against each other and the upper portion of a continental plate splits from the deeper rocks. A portion of the upper crust, usually several miles thick, begins to move slowly across the continent. Ultimately it runs into another mass, creating a ramp. This can result in unusually singular mountains, such as Chief Mountain in Montana, which slid across open prairie on a thrust sheet.

Under the ocean is the longest mountain chain on Earth, the mid-ocean ridge system, which runs down the center of the Atlantic Ocean and continues through the Indian and Pacific oceans. Lava continuously erupts along this ridge, releasing geothermal energy and opening up new strips of ocean floor. This brings us to a special kind of mountain, typically resulting from the sort of dramatic plate tectonic processes that also produce earthquakes: volcanoes.

VOLCANOES

Most volcanoes are mountains, and for this reason, it is appropriate to discuss them together; however, a volcano is not necessarily a mountain. A volcano may be defined as a natural opening in Earth's surface through which molten (liquid), solid, and gaseous material erupts. The word *volcano* also is used to describe the cone of erupted material that builds up around the opening or fissure. Because these cones are often quite impressive in height, they frequently are associated with mountains.



THE POPOCATEPETL VOLCANO ERUPTS, SPEWING ASH, ROCKS, AND GASES. *(© Wesley Bocxe/Photo Researchers. Reproduced by permission.)*

Though volcanic activity has been the case of death and destruction, it is essential to the planet's survival. Volcanic activity is the principal process through which chemical elements, minerals, and other compounds from Earth's interior reach its surface. These substances, such as carbon dioxide, have played a major role in the development of the planet's atmosphere, waters, and soils. Even today, soil in volcanic areas is among the richest on Earth. Volcanoes provide additional benefits in their release of geothermal energy, used for heating and other purposes in such countries as Iceland, Italy, Hungary, and New Zealand (see Energy and Earth). In addition, volcanic activity beneath the oceans promises to supply almost limitless geothermal energy,

once the technology for its extraction becomes available.

Formation of volcanoes. As noted earlier, land volcanoes are formed in coastal areas where continental and oceanic plates converge. As the oceanic plate is subducted and pushed farther and farther beneath the continental surface, the buildup of heat and pressure results in the melting of rock. This molten rock, or magma, tends to rise toward the surface and collect in magma reservoirs. Pressure buildup in the magma reservoir ultimately pushes the magma upward through cracks in Earth's crust, creating a volcano.

Volcanoes also form underwater, in which case they are called seamounts. Convergence of oceanic plates causes one plate to sink beneath the other, creating an oceanic trench; as a result, magma rises from the subducted plate to fashion volcanoes. If the plates diverge, magma seeps upward at the ridge or margin between plates, producing more seafloor. This process, known as seafloor spreading, leads to the creation of volcanoes on either side of the ridge.

In some places a plate slides over a stationary area of volcanic activity, known as a hot spot. These are extremely hot plumes of magma that well up from the crust, though not on the edge or margin of a plate. A tectonic plate simply drifts across the hot spot, and as it does, the area just above the hot spot experiences volcanic activity. Hot spots exist in Hawaii, Iceland, Samoa, Bermuda, and America's Yellowstone National Park.

Classifying volcanoes. Volcanoes can be classified in terms of their volcanic activity, in which case they are labeled as active (currently erupting), dormant (not currently erupting but likely to do so in the future), or extinct. In the case of an extinct volcano, no eruption has been noted in recorded history, and it is likely that the volcano has ceased to erupt permanently.

In terms of shape, volcanoes fall into four categories: cinder cones, composite cones, shield volcanoes, and lava domes. These types are distinguished not only by morphologic characteristics but also by typical sizes and even angles of slope. For instance, cinder cones, built of lava fragments, have slopes of 30° to 40°, and are seldom more than 1,640 ft. (500 m) in height.

Composite cones, or stratovolcanoes, are made up of alternating layers of lava (cooled magma), ash, and rock. (The prefix *strato* refers to these layers.) They may slope as little as 5° at the base and as much as 30° at the summit. Stratovolcanoes may grow to be as tall as 2–3 mi. (3.2–4.8 km) before collapsing and are characterized by a sharp, dramatic shape. Examples include Fuji, a revered mountain that often serves as a symbol of Japan, and Washington state's Mount Saint Helens.

A shield volcano, which may be a solitary formation and often is located over a hot spot, is built from lava flows that pile one on top of another. With a slope as little as 2° at the base and no more than 10° at the summit, shield volcanoes are much wider than stratovolcanoes, but sometimes they can be impressively tall. Such is the case with Mauna Loa in Hawaii, which at 13,680 ft. (4,170 m) above sea level is the world's largest active volcano. Likewise, Mount Kilimanjaro, though long ago gone dormant, is the tallest mountain in Africa.

Finally, there are lava domes, which are made of solid lava that has been pushed upward. Closely related is a volcanic neck, which often forms from a cinder cone. In the case of a volcanic neck, lava rises and erupts, leaving a mountain that looks like a giant gravel heap. Once it has become extinct, the lava inside the volcano begins to solidify. Over time the rock on the exterior wears away, leaving only a vent filled with solidified lava, usually in a funnel shape. A dramatic example of this appears at Shiprock, New Mexico.

Volcanic eruptions. Volcanoes frequently are classified by the different ways in which they erupt. These types of eruption, in turn, result from differences in the material being disgorged from the volcano. When the magma is low in gas and silica (silicon dioxide, found in sand and rocks), the volcano erupts in a relatively gentle way. Its lava is thin and spreads quickly. Gas and silica–rich magma, on the other hand, brings about a violent explosion that yields tarlike magma.

There are four basic forms or phases of volcanic eruption: Hawaiian, Strombolian, Vulcanian, and Peleean. The Hawaiian phase is simply a fountain-like gush of runny lava, without any explosions. The Strombolian phase (named after a volcano on a small island off the Italian penin-



Crater Lake in Oregon is the result of the collapse of a magma chamber after a volcanic eruption. This collapse forms a bowl-like crater called a caldera, which fills with water. *(© Francois Gohier/Photo Researchers. Reproduced by permission.)*

sula) involves thick lava and mild explosions. In a Vulcanian phase, magma has blocked the volcanic vent, and only after an explosion is the magma released, with the result that tons of solid material and gases are hurled into the sky. Most violent of all is the Peleean, named after Mount Pelée on Martinique in the Caribbean (discussed later). In the Peleean phase, the volcano disgorges thick lava, clouds of gas, and fine ash, all at formidable velocities.

Accompanying a volcanic eruption in many cases are fierce rains, the result of the expulsion of steam from the volcano, after which the steam condenses in the atmosphere to form clouds. Gases thrown into the atmosphere are often volatile and may include hydrogen sulfide, fluorine, carbon dioxide, and radon. All are detrimental to human beings when present in sufficient quantity, and radon is radioactive.

Not surprisingly, the eruption of a volcano completely changes the morphologic characteristics of the landform. During the eruption a crater is formed, and out of this flows magma and ash, which cool to form the cone. In some cases, the magma chamber collapses just after the eruption, forming a caldera, or a large, bowl-shaped crater. These caldera (the plural as well as singular form) may fill with water, as was the case at Oregon's Crater Lake.

INFAMOUS VOLCANIC DISASTERS. Volcanoes result from some of the same tectonic forces as earthquakes (see Seismology), and, not surprisingly, they often have resulted in enormous death and destruction. Some remarkable examples include:

- *Vesuvius, Italy, A.D. 79 and 1631:* Situated along the Bay of Naples in southern Italy, Vesuvius has erupted more than 50 times during the past two millennia. Its most famous eruption occurred in A.D. 79, when the Roman Empire was near the height of its power. The first-century eruption buried the nearby towns of Pompeii and Herculaneum, where bodies and buildings were preserved virtually intact until excavation of the area in 1748. Another eruption, in 1631, killed some 4,000 people.
- *Krakatau, Indonesia, A.D. 535 (?) and 1883:* The most famous eruption of Krakatau occurred in 1883, resulting in the loss of some 36,000 lives. The explosion, which was heard 3,000 mi. away, threw 70-lb. (32-kg) boulders as far as 50 mi. (80 km). It also produced a tsunami, or tidal wave, 130 ft.

(40 m) high, which swept away whole villages. In addition, the blast hurled so much dust into the atmosphere that the Moon appeared blue or green for two years. It is also possible that Krakatau erupted in about A.D. 535, causing such a change in the atmosphere that wide areas of the world experienced years without summer. (See Earth Systems for more on this subject.)

- *Tambora, Indonesia, 1815:* Another Indonesian volcano, Tambora, killed 12,000 people when it erupted in 1815. As with Krakatau in 535, this eruption was responsible for a year without summer in 1816 (see Earth Systems).
- *Pelée, Martinique, 1902:* When Mount Pelée erupted on the Caribbean island of Martinique, it sent tons of poisonous gas and hot ash spilling over the town of Saint-Pierre, killing all but four of its 29,937 residents.
- *Saint Helens, Washington, 1980:* Relatively small compared with earlier volcanoes, the Mount Saint Helens blast is still significant because it was so recent and took place in the United States. The eruption sent debris flying upward 1,300 ft. (396 m) and caused darkness over towns as far as 85 mi. (137 km) away. Fifty-seven people died in the eruption and its aftermath.
- *Pinatubo, Philippines, 1991:* Dormant for 600 years, Mount Pinatubo began to rumble one day in 1991 and, after a few days, erupted in a cloud that spread ash 6 ft. (1.83 m) deep along a radius of 2 mi. (3.2 km). A U.S. air base 15 mi. (24 km) away was buried. The blast threw 20 million tons (18,144,000 metric tons) of sulfuric acid 12 mi. (19 km) into the stratosphere, and the cloud ultimately covered the entire planet, resulting in moderate cooling for a few weeks.

The Impact of Mountains

Volcanic eruptions are among the most dramatic effects produced by mountains, but they are far from the only ones. Every bit as fascinating are the effects mountains produce on the weather, on the evolution of species, and on human society. In each case, mountains serve as a barrier or separator—between masses of air, clouds, and populations.

Wind pushes air and moisture-filled clouds up mountain slopes, and as the altitude increases, the pressure decreases. As a result, masses of warm, moist air become larger, cooler, and less dense. This phenomenon is known as *adiabatic expansion,* and it is the same thing that happens when an aerosol can is shaken, reducing the pressure of gases inside and cooling the surface of the can. Under the relatively high-pressure and high-temperature conditions of the flatlands, water exists as a gas, but in the heights of the mountaintops, it cools and condenses, forming clouds.

RAIN SHADOWS. As the clouds rise along the side of the mountain, they begin to release heavy droplets in the form of rain and, at higher altitudes, snow. By the time the cloud crosses the top of the mountain, however, it will have released most of its moisture, and hence the other side of the mountain may be arid. The leeward side, or the side opposite the wind, becomes what is called a rain shadow.

Although they are only 282 mi. (454 km) apart, the cities of Seattle and Spokane, Washington, have radically different weather patterns. Famous for its almost constant rain, Seattle lies on the windward, or wind-facing, side of the Cascade Range, toward the Pacific Ocean. On the leeward side of the Cascades is Spokane, where the weather is typically warm and dry. Though it is only on the other side of the state, Spokane might as well be on the other side of the continent. Indeed, it is associated more closely with the arid expanses of Idaho, whereas Seattle belongs to a stretch of cold, wet Pacific terrain that includes San Francisco and Portland, Oregon.

Much of the western United States consists of deserts formed by rain shadows or, in some cases, double rain shadows. Much of New Mexico, for instance, lies in a double rain shadow created by the Rockies in the west and Mexico's Sierra Madres to the south. In southern California, tall redwoods line the lush windward side of the Sierra Nevadas, while Death Valley and the rest of the Mojave Desert lies in the rain shadow on the eastern side. The Great Basin that covers eastern Oregon, southern Idaho, much of Utah, and almost all of Nevada, likewise is created by the rain shadow of the Sierra Nevada-Cascade chain.

MOUNTAINS AND SPECIES. One of the most intriguing subjects involved in the study of mountains is their effects on large

KEY TERMS

ACTIVE: A term to describe a volcano that is currently erupting.

COMPRESSION: A form of stress produced by the action of equal and opposite forces, the effect of which is to reduce the length of a material. Compression is a form of pressure.

CONVERGENCE: A tectonic process whereby plates move toward each other.

CRUST: The uppermost division of the solid earth, representing less than 1% of its volume and varying in depth from 3 mi. to 37 mi. (5–60 km). Below the crust is the mantle.

DIVERGENCE: A tectonic process whereby plates move away from each other.

DORMANT: A term to describe a volcano that is not currently erupting but is likely to do so in the future.

EPEIROGENESIS: One of two principal forms of tectonism, the other being orogenesis. Derived from the Greek words *epeiros* ("mainland") and *genesis* ("origins"), epeirogenesis takes the form of either uplift or subsidence.

EXTINCT: A term to describe a volcano for which no eruption has been known in recorded history. In this case, it is likely that the volcano has ceased to erupt permanently.

GEOMORPHOLOGY: An area of physical geology concerned with the study of landforms, with the forces and processes that have shaped them, and with the description and classification of various physical features on Earth.

HOT SPOT: A region of high volcanic activity.

LANDFORM: A notable topographical feature, such as a mountain, plateau, or valley.

LITHOSPHERE: The upper layer of Earth's interior, including the crust and the brittle portion at the top of the mantle.

MANTLE: The thick, dense layer of rock, approximately 1,429 mi. (2,300 km) thick, between Earth's crust and its core.

MORPHOLOGY: Structure or form or the study thereof.

MOUNTAIN CHAIN: A series of ranges stretching across a continent for a great distance.

MOUNTAIN MASS: An irregular grouping of mountains, which lacks the broad linear sweep of a range or chain.

MOUNTAIN RANGE: A relatively localized series of peaks and ridges.

MOUNTAIN SYSTEM: A combination of ranges, chains, and masses of mountains that stretches across vast distances, usually encompassing more than one continent.

OROS: A Greek word meaning "mountain," which appears in such words as *orogeny,* a variant of *orogenesis; orogen,* another term for "mountain" and *orogenic,* as in "orogenic belt."

OROGENESIS: One of two principal forms of tectonism, the other being epeirogenesis. Derived from the Greek words *oros* ("mountain") and *genesis* ("origin"), orogenesis involves the formation of mountain ranges by means of folding, faulting, and volcanic activity. The processes of orogenesis play a major role in plate tectonics.

PLATE MARGINS: Boundaries between plates.

KEY TERMS CONTINUED

PLATE TECTONICS: The name both of a theory and of a specialization of tectonics. As an area of study, plate tectonics deals with the large features of the lithosphere and the forces that shape them. As a theory, it explains the processes that have shaped Earth in terms of plates and their movement.

PLATES: Large, movable segments of the lithosphere.

SHEAR: A form of stress resulting from equal and opposite forces that do not act along the same line. If a thick, hardbound book is lying flat, and one pushes the front cover from the side so that the covers and pages are no longer aligned, this is an example of shear.

STRAIN: The ratio between the change in dimension experienced by an object that has been subjected to stress and the original dimensions of the object.

STRESS: In general terms, any attempt to deform a solid. Types of stress include tension, compression, and shear.

SUBSIDENCE: A term that refers either to the process of subsiding, on the part of air or solid earth, or, in the case of solid earth, to the resulting formation. Subsidence thus is defined variously as the downward movement of air, the sinking of ground, or a depression in Earth's crust.

TECTONICS: The study of tectonism, including its causes and effects, most notably mountain building.

TECTONISM: The deformation of the lithosphere.

TENSION: A form of stress produced by a force that acts to stretch a material.

TOPOGRAPHY: The configuration of Earth's surface, including its relief as well as the position of physical features.

UPLIFT: A process whereby the surface of Earth rises, as the result of either a decrease in downward force or an increase in upward force.

VOLCANO: A natural opening in Earth's surface through which molten (liquid), solid, and gaseous material erupts. The word volcano is also used to describe the cone of erupted material that builds up around the opening or fissure.

groups of plants, animals, and humans. Mountains may separate entire species, creating pockets of flora and fauna virtually unknown to the rest of the world. Thus, during the 1990s, huge numbers of species that had never been catalogued were discovered in the mountains of southeast Asia.

The formation of mountains and other landforms may even lead to speciation, a phenomenon in which members of a species become incapable of reproducing with other members, thus creating a new species. When the Colorado River cut open the Grand Canyon, it separated groups of squirrels that lived in the high-altitude pine forest. Over time these populations ceased to interbreed, and today the Kaibab squirrel of the north rim and the Abert squirrel of the south are separate species, no more capable of interbreeding than humans and apes.

HUMAN SOCIETIES AND MOUNTAINS. Although the Appalachians of the eastern United States are hundreds of millions of years old, most ranges are much younger. Most will erode or otherwise cease to exist in a relatively short time (short, that is, by geologic standards), yet to humans throughout the ages,

mountains have seemed a symbol of permanence. This is just one aspect of mountains' impact on the human psyche.

In his 1975 study of symbolism in political movements, *Utopia and Revolution,* Melvin J. Lasky devoted considerable space to the mountain and its association with divinity through figures such as the Greek Olympians and Noah and Moses in the Bible. Clearly, mountains have proved enormously influential on human attitudes, and nowhere is this more obvious than in relation to the people who live *in* the mountains. Whether the person is a coal miner from Appalachia or a rancher from the Rockies, a Scottish highlander or a Quechua-speaking Peruvian, the mentality is similar, characterized by a combination of hardiness, fierce independence, and disdain for lowland ways.

These characteristics, combined with the harsh weather of the mountains, have made mountain warfare a challenge to lowland invaders. This explains the fact that Switzerland has kept itself free from involvement in European wars since Napoleon's time, and why the independent Scottish Highlands were long a thorn in England's side. It also explains why neither the British nor the Russian empires could manage to control Afghanistan fully during their struggle over that mountainous nation in the late nineteenth and early twentieth centuries.

Britain eventually pulled out of the "Great Game," as this struggle was called, but Russia never really did. Many years later, the Soviets became bogged down in a war in Afghanistan that they could not win. The war, which lasted from 1979 to 1989, helped bring about the end of the Soviet Union and its system of satellite dictatorships. More than a decade later, as the United States launched strikes against Afghanistan in 2001, a superpower once again faced the challenge posed by one of the poorest, most inhospitable nations on Earth.

But the independence of the mountaineer is deceptive; in fact, mountains have little to offer, economically, other than their beauty and the resources deep beneath their surfaces. In other words, they are really of value only to flatland tourists and mining companies. Since few mountain environments offer much promise agriculturally, the people of the mountains are dependent on the flatlands for sustenance. Gorgeous and rugged as they are, such mountainous states as Colorado or Wyoming might be as poor as Afghanistan were it not for the fact that they belong to a larger political unit, the United States.

WHERE TO LEARN MORE

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EROSION

CONCEPT

Erosion is a broadly defined group of processes involving the movement of soil and rock. This movement is often the result of flowing agents, whether wind, water, or ice, which sometimes behaves like a fluid in the large mass of a glacier. Gravitational pull may also influence erosion. Thus, erosion, as a concept in the earth sciences, overlaps with mass wasting or mass movement, the transfer of earth material down slopes as a result of gravitational force. Even more closely related to erosion is weathering, the breakdown of rocks and minerals at or near the surface of Earth owing to physical, chemical, or biological processes. Some definitions of erosion even include weathering as an erosive process. Though most widely known as a by-product of irresponsible land use by humans and for its negative effect on landforms, erosion is neither unnatural nor without benefit. Far more erosion occurs naturally than as a result of land development, and a combination of weathering and erosion is responsible for producing the soil from which Earth's plants grow.

HOW IT WORKS

Weathering

The first step in the process of erosion is weathering. Weathering, in a general sense, occurs everywhere: paint peels; metal oxidizes, resulting in its tarnishing or rusting; and any number of products, from shoes to houses, begin to show the effects of physical wear and tear. The scuffing of a shoe, cracks in a sidewalk, or the chipping of glass in a gravel-spattered windshield are all examples of physical weathering. On the other hand, the peeling of paint is usually the result of chemical changes, which have reduced the adhesive quality of the paint. Certainly oxidation is a chemical change, meaning that it has not simply altered the external properties of the item but also has brought about a change in the way that the atoms are bonded.

Weathering, as the term is used in the geologic sciences, refers to these and other types of physical and chemical changes in rocks and minerals at or near the surface of Earth. A mineral is a substance that occurs naturally and is usually inorganic, meaning that it contains carbon in a form other than that of an oxide or a carbonate, neither of which is considered organic. It typically has a crystalline structure, or one in which the constituent parts have a simple and definite geometric arrangement repeated in all directions. Rocks are simply aggregates or combinations of minerals or organic material or both.

TWO AND ONE-HALF KINDS OF WEATHERING. There are three kinds of weathering (or perhaps two and one-half, since the third incorporates aspects of the first two): physical or mechanical, chemical, and biological. Physical or mechanical weathering takes place as a result of such factors as gravity, friction, temperature, and moisture. Gravity may cause a rock to drop from a height, such that it falls to the ground and breaks into pieces, while the friction of wind-borne sand may wear down a rock surface. Changes in temperature and moisture cause expansion and contraction of materials, as when water seeps into a crack in a rock and then freezes, expanding and splitting the rock.



Nicola River Canyon in British Columbia shows the effects of freeze-thaw and erosion by wind and rain. *(© K. Svensson/Photo Researchers. Reproduced by permission.)*

Minerals are chemical compounds; thus, whereas physical weathering attacks the rock as a whole, chemical weathering effects the breakdown of the minerals that make up the rock. This breakdown may lead to the dissolution of the minerals, which then are washed away by water or wind or both, or it may be merely a matter of breaking the minerals down into simpler compounds. Reactions that play a part in this breakdown may include oxidation, mentioned earlier, as well as carbonation, hydrolysis (a reaction with water that results in the separation of a compound to form a new substance or substances), and acid reactions. For instance, if coal has been burned in an area, sulfur impurities in the air react with water vapor (an example of hydrolysis) to produce acid rain, which can eat away at rocks. Rainwater itself is a weak acid, and over the years it slowly dissolves the marble of headstones in old cemeteries.

As noted earlier, there are either three or two and one-half kinds of weathering, depending on whether one considers biological weathering a third variety or merely a subset of physical and chemical weathering. The weathering exerted by organisms (usually plants rather than animals) on rocks and minerals is indeed chemical and physical, but because of the special circumstances, it is useful to consider it individually. There is likely to be a long-term interaction between the organism and the geologic item, an obvious example being a piece of moss that grows on a rock. Over time, the moss will influence both physical and chemical weathering through its attendant moisture as well as its specific chemical properties, which induce decomposition of the rock's minerals.

Unconsolidated Material

The product of weathering in rocks or minerals is unconsolidated, meaning that it is in pieces, like gravel, though much less uniform in size. This is called regolith, a general term that describes a layer of weathered material that rests atop bedrock. Sand and soil, including soil mixed with loose rocks, are examples of regolith. Regolith is, in turn, a type of sediment, material deposited at or near Earth's surface from a number of sources, most notably preexisting rock.

Every variety of unconsolidated material has its own angle of repose, or the maximum angle at which it can remain standing. Piles of rocks may have an angle of repose as high as 45°, whereas dry sand has an angle of only 34°. The addition of water can increase the angle of repose, as anyone who has ever strengthened a sand castle by

adding water to it knows. Suppose one builds a sand castle in the morning, sloping the sand at angles that would be impossible if it were dry. By afternoon, as wind and sunlight dry out the sand, the sand castle begins to fall apart, because its angle of repose is too high for the dry sand.

Water gives sand surface tension, the same property that causes water that has been spilled on a table to bead up rather than lie flat. If too much water is added to the sand, however, the sand becomes saturated and will flow, a process called lateral spreading. On the other hand, with too little moisture, the material is susceptible to erosion. Unconsolidated material in nature generally has a slope less than its angle of repose, owing to the influence of wind and other erosive forces.

Introduction to Mass Wasting

There are three general processes whereby a piece of earth material can be moved from a high outcropping to the sea: weathering, mass wasting, and erosion. In the present context, we are concerned primarily with the last of these processes, of course, and secondarily with weathering, inasmuch as it contributes to erosion. A few words should be said about mass wasting, however, which, in its slower forms (most notably, creep), is related closely to erosion.

Mechanical or chemical processes, or a combination of the two, acting on a rock to dislodge it from a larger sample (e.g., separating a rock from a boulder) is an example of weathering, as we have seen. If the pieces of rock are swept away by a river in a valley below the outcropping, or if small pieces of rock are worn away by high winds, the process is erosion. Between the outcropping and the river below, if a rock has been broken apart by weathering, it may be moved farther along by mass-wasting processes, such as creep or fall.

REAL-LIFE APPLICATIONS

Mass Wasting in Action

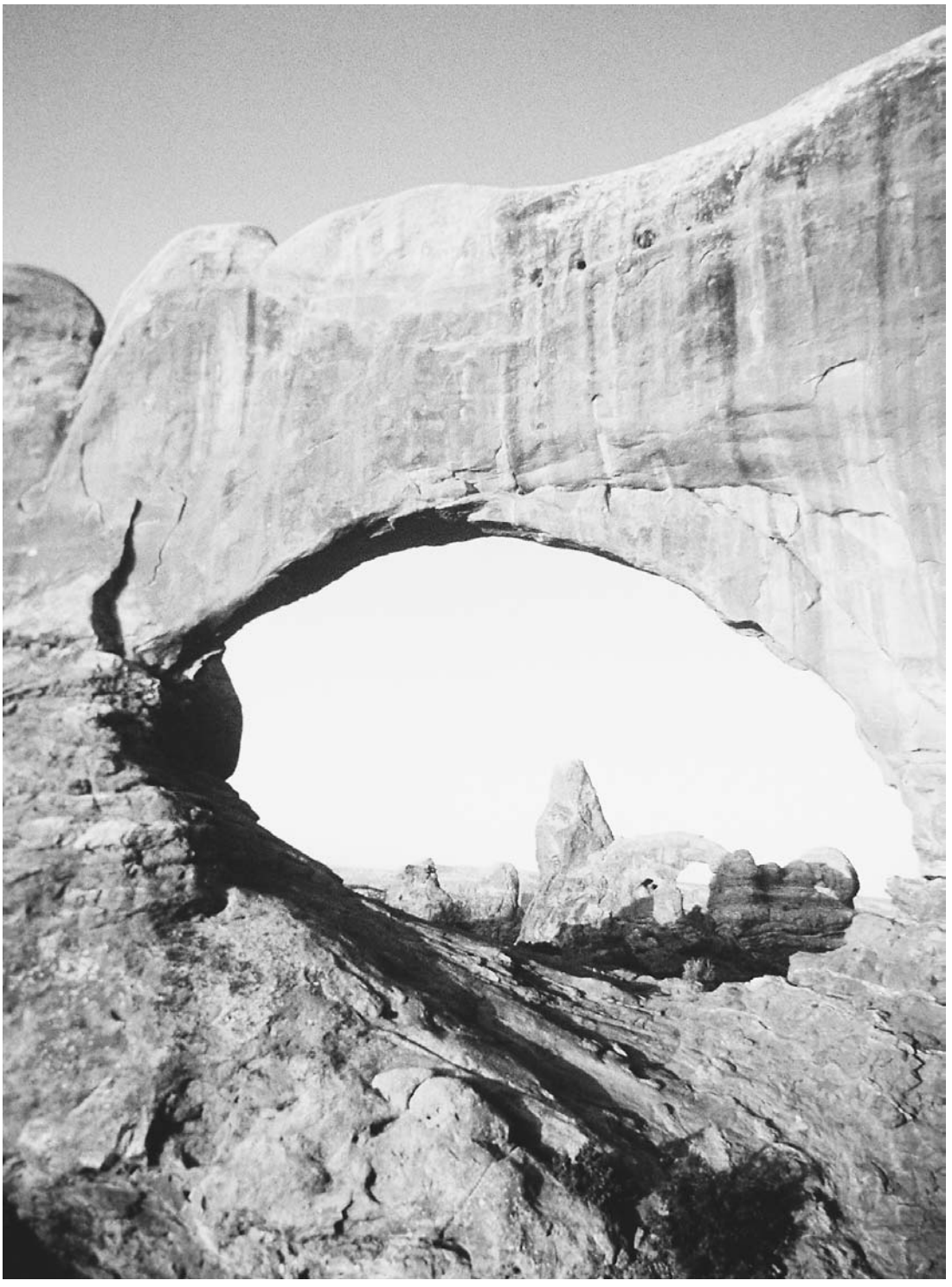
One of the principal sources of erosion is gravity, which is also the force behind creep, the slow downward movement of regolith along a hill slope. The regolith begins in a condition of unstable equilibrium, like a soda can lying on its side rather than perpendicular to a table's surface: in both cases, the object remains in place, yet a relatively small disturbance would be enough to dislodge it.

Changes in temperature or moisture are among the leading factors that result in creep. A variation in either can cause material to expand or contract, and freezing or thawing may be enough to shake regolith from its position of unstable equilibrium. Water also can provide lubrication, or additional weight, that assists the material in moving. Though it is slow, over time creep can produce some of the most dramatic results of any mass-wasting process. It can curve tree trunks at the base, break or dislodge retaining walls, and overturn objects ranging from fence posts to utility poles to tombstones.

Other varieties of flow. Creep is related to another slow mass-wasting process, known as solifluction, that occurs in the active layer of permafrost—that is, the layer that thaws in the summertime. The principal difference between creep and solifluction is not the speed at which they take place (neither moves any faster than about 0.5 in. [1 cm] per year) but the materials involved. Both are examples of flow, a chaotic form of mass wasting in which masses of material that are not uniform move downslope. With the exception of creep and solifluction, most forms of flow are comparatively rapid, and some are extremely so.

Because it involves mostly dry material, creep is an example of granular flow, which is composed of 0% to 20% water; on the other hand, solifluction, because of the ice component, is an instance of slurry flow, consisting of 20% to 40% water. If the water content is more than 40%, a slurry flow is considered a stream. Types of granular flow that move faster than creep range from earth flow to debris avalanche. Both earth flow and debris flow, its equivalent in slurry form, move at a broad range of speeds, anywhere from about 4 in. (10 cm) per year to 0.6 mi. (1 km) per *hour.* Grain flow can be as fast as 60 mi. (100 km) per hour, and mud flow is even faster. Fastest of all is debris avalanche, which may achieve speeds of 250 mi. (400 km) per hour.

Other types of mass wasting. Other varieties of mass wasting include slump, slide, and fall. Slump occurs when a mass of regolith slides over or creates a concave surface



Rock arches formed by erosion. *(© N. R. Rowan/Photo Researchers. Reproduced by permission.)*

(one shaped like the inside of a bowl.) The result is the formation of a small, crescent-shaped cliff, known as a scarp, at the upper end—rather like the crest of a wave. Slump often is classified as a variety of slide, in which material moves downhill in a fairly coherent mass (i.e., more or less in a section or group) along a flat or planar surface. These movements are sometimes called rock slides, debris slides, or, in common parlance, landslides.

In contrast to most other forms of mass wasting, in which there is movement along slopes

that are considerably less than 90°, fall occurs at angles almost perpendicular to the ground. The "Watch for Falling Rock" signs on mountain roads may be frightening, and rock or debris fall is certainly one of the more dramatic forms of mass wasting. Yet the variety of mass wasting that has the most widespread effects on the morphology or shape of landforms is the slowest one—creep. (For more about the varieties of mass wasting, see Mass Wasting.)

What Causes Erosion?

As noted earlier, the influences behind erosion are typically either gravity or flowing media: water, wind, and even ice in glaciers. Liquid water is the substance perhaps most readily associated with erosion. Given enough time, water can wear away just about anything, as proved by the carving of the Grand Canyon by the Colorado River.

Dubbed the *universal solvent* for its ability to dissolve other materials, water almost never appears in its pure form, because it is so likely to contain other substances. Even "pure" mountain water contains minerals and pieces of the rocks over which it has flowed, a testament to the power of water in etching out landforms bit by bit. Nor does it take a rushing mountain stream or crashing waves to bring about erosion; even a steady drip of water is enough to wear away granite over time.

Moving water. Along coasts, pounding waves continually alter the shoreline. The sheer force of those walls of water, a result of the Moon's gravitational pull (and, to a lesser extent, the Sun's), is enough to wear away cliffs, let alone beaches. In addition, waves carry pieces of pebble, stone, and sand that cause weathering in rocks. Waves even can bring about small explosions in pockmarked rock surfaces by trapping air in small cracks; eventually the pressure becomes great enough that the air escapes, loosening pieces of the rock.

In addition to the erosive power of saltwater waves on the shore, there is the force exerted by running water in creeks, streams, and rivers. As the river moves, pushing along sediment and other materials eroded from the streambed or riverbed, it carves out deep chasms in the bedrock beneath. These moving bodies of water continually reshape the land, carrying soil and debris downslope, or from the source of the river to its mouth or delta. A delta is a region of sediment formed when a river enters a larger body of water, at which point the reduction in velocity on the part of the river current leads to the widespread deposition (depositing) of sediment. It is so named because its triangular shape resembles that of the Greek letter delta, Δ.

Water at the bottom of a large body, such as a pond or lake, also exerts erosive power. Then there is the influence of falling rain. Assuming ground is not protected by vegetation, raindrops can loosen particles of soil, sending them scattering in all directions. A rain that is heavy enough may dislodge whole layers of topsoil and send them rushing away in a swiftly moving current. The land left behind may be rutted and scarred, much of its best soil lost for good.

Just as erosion gives to the soil, it also can take away. Whereas erosion on the Nile delta acted to move rich, black soil into the region (hence, the ancient Egyptians' nickname for their country, the "black land"), erosion also can remove soil layers. As is often the case, it is much easier to destroy than to create: 1 in. (2.5 cm) of soil may take as long as 500 years to form, yet a single powerful rainstorm or windstorm can sweep it away.

Glaciers

Ice, of course, is simply another form of water, but since it is solid, its physical (*not* its chemical) properties are quite different. Generally, physical sciences, such as physics or chemistry, treat as fluid all forms of matter that flow, whether they are liquid or gas. Normally, no solids are grouped under the heading of "fluid," but in the earth sciences there is at least one type of solid object that behaves as though it were fluid: a glacier.

A glacier is a large, typically moving mass of ice either on or adjacent to a land surface. It does not flow in the same way that water does; rather, it is moved by gravity, as a consequence of its extraordinary weight. Under certain conditions, a glacier may have a layer of melted water surrounding it, which greatly enhances it mobility. Regardless of whether it has this lubricant, however, a glacier steadily moves forward, carrying pieces of rock, soil, and vegetation with it.

These great rivers of ice gouge out pieces of bedrock from mountain slopes, fashioning deep valleys. Ice along the bottom of the glacier pulls away rocks and soil, which assist it in wearing



A "dust devil," or a small whirlwind, carries with it debris and sand. *(© Clem Haagner/Photo Researchers. Reproduced by permission.)*

away bedrock. The fjords of Norway, where high cliffs surround narrow inlets whose depths extend many thousands of feet below sea level, are a testament to the power of glaciers in shaping the Earth. The fact that the fjords came into existence only in the past two million years, a product of glacial activity associated with the last ice age, is evidence of something else remarkable about glaciers: their speed.

"Speed," of course, is a relative term when speaking about processes involved in the shaping of the planet. A "fast" glacier, one whose movement is assisted by a wet and warm (again, *relatively* warm!) maritime climate, moves at the rate of about 980 ft. (300 m) per year. Examples include not only the glaciers that shaped the fjords, but also the active Franz Josef glacier in southern New Zealand. By contrast, in the dry, exceptionally cold, inland climate of Antarctica, the Meserve glacier moves at the rate of just 9.8 ft. (3 m) per year.

Wind

The erosion produced by wind often is referred to as an eolian process, the name being a reference to Aeolus, the Greek god of the winds encountered in Homer's *Odyssey* and elsewhere. Eolian processes include the erosion, transport, and deposition of earth material owing to the action of wind. It is most pronounced in areas that lack effective ground cover in the form of solidly rooted, prevalent vegetation.

Eolian erosion in some ways is less forceful than the erosive influence of water. Water, after all, can lift heavier and larger particles than can the winds. Wind, however, has a much greater frictional component in certain situations. This is particularly true when the wind carries sand, every grain of which is like a cutting tool. In some desert regions the bases of rocks or cliffs have been sandblasted, leaving a mushroom-shaped formation. The wind could not lift the fine grains of sand very high, but in places where it has been able to do its work, it has left an indelible mark.

The Dust Bowl and Human Contribution to Erosion

Though human actions are not a direct cause of erosion, human negligence or mismanagement often has prepared the way for erosive action by wind, water, or other agents. Interesting, soil itself, formed primarily by chemical weathering and enhanced by biological activity in the sediment, is a product of nature's erosive powers. Erosion transports materials from one place to another, robbing the soil in one place and greatly enhancing it in another.

This is particularly the case where river deltas are concerned. By transporting sediment and depositing it in the delta, the river creates an area of extremely fertile soil that, in some cases, has become literally the basis for civilizations. The earliest civilizations of the Western world, in Egypt and Sumer, arose in the deltas of the Nile and the Tigris-Euphrates river systems, respectively.

Erosion on the Great Plains. An extreme example of the negative effects on the soil that can come from erosion (and, ultimately, from human mismanagement) took place in Texas, Oklahoma, Colorado, and Kansas during the 1930s. In the preceding years, farmers unwittingly had prepared the way for vast erosion by overcultivating the land and not taking proper steps to preserve its moisture against drought. In some places farmers alternated between wheat cultivation and livestock grazing on particular plots of land.

The soil, already weakened by raising wheat, was damaged further by the hooves of livestock, and thus when a period of high winds began at the height of the Great Depression (1929–41), the land was particularly vulnerable. The winds carried dust to places as far away as the eastern seaboard, in some cases removing topsoil to a depth of 3–4 in. (7–10 cm). Dunes of dust as tall as 15–20 ft. (4.6–6.1 m) formed, and the economic blight of the Depression was compounded for the farmers of the plains states, many of whom lost everything.

Out of the Dust Bowl era came some of the greatest American works of art: the 1939 film *Wizard of Oz,* John Steinbeck's book *The Grapes of Wrath* and the acclaimed motion picture (1939 and 1940, respectively), as well as Dorothea Lange's haunting photographs of Dust Bowl victims. The Dust Bowl years also taught farmers and agricultural officials a lesson about land use, and in later years farming practices changed. Instead of alternating one year of wheat growing with one year in which a field lay fallow, or unused, farmers discovered that a wheat-sorghum-fallow cycle worked better. They also enacted other measures, such as the planting of trees to serve as windbreaks around croplands.

The Striking Landscape of Erosion

Among the by-products of erosion are some of the most dramatic landscapes in the world, many of which are to be found in the United States. A particularly striking example appears in Colorado, where the Arkansas River carved out the Royal Gorge. Though it is not nearly as deep as the Grand Canyon, this one has something the more famous gorge does not: a bridge. Motorists with the stomach for it can cross a span 1,053 ft. (0.32 km) above the river, one of the most harrowing drives in America.

Another, perhaps equally taxing, drive is that down California 1, a gorgeous scenic highway whose most dramatic stretches lie between Carmel and San Simeon. Drivers headed south find themselves pressed up against the edge of the cliffs, such that the slightest deviation from the narrow road would send an automobile and its passengers plummeting to the rocks many hundreds of feet below. These magnificent, terrifying landforms are yet another product of erosion, in this case, the result of the pounding Pacific waves.

Also striking is the topography produced by the erosion of material left over from a volcanic eruption. As discussed in the Mountains essay, Devils Tower National Monument in Wyoming is

KEY TERMS

CREEP: A form of mass wasting involving the slow downward movement of regolith as a result of gravitational force.

DELTA: A region of sediment formed when a river enters a larger body of water, at which point the reduction in velocity on the part of the river current leads to the widespread deposition of sediment.

DEPOSITION: The process whereby sediment is laid down on the Earth's surface.

EROSION: The movement of soil and rock due to forces produced by water, wind, glaciers, gravity, and other influences. In most cases, a fluid medium, such as air or water, is involved.

FLOW: A form of mass wasting in which a body of material that is not uniform moves rapidly downslope.

GEOMORPHOLOGY: An area of physical geology concerned with the study of landforms, with the forces and processes that have shaped them, and with the description and classification of various physical features on Earth.

GLACIER: A large, typically moving mass of ice either on or adjacent to a land surface.

LANDFORM: A notable topographical feature, such as a mountain, plateau, or valley.

MASS WASTING: The transfer of earth material, by processes that include creep, slump, slide, flow, and fall, down slopes. Also known as *mass movement.*

MORPHOLOGY: Structure or form or the study thereof.

REGOLITH: A general term describing a layer of weathered material that rests atop bedrock.

SEDIMENT: Material deposited at or near Earth's surface from a number of sources, most notably preexisting rock.

SLIDE: A variety of mass wasting in which material moves downhill in a fairly coherent mass (i.e., more or less in a section or group) along a flat or planar surface.

SLUMP: A form of mass wasting that occurs when a mass of regolith slides over or creates a concave surface (one shaped like the inside of a bowl).

TOPOGRAPHY: The configuration of Earth's surface, including its relief as well as the position of physical features.

WEATHERING: The breakdown of rocks and minerals at or near the surface of Earth due to physical, chemical, or biological processes.

the remains of an extinct volcano whose outer surface long ago eroded, leaving just the hard lava of the volcanic "neck." Erosion of lava also can produce mesas. Lava that has settled in a river valley may be harder than the rocks of the valley walls, such that the river eventually erodes the rocks, leaving only the lava platform. What was once the floor of the valley thus becomes the top of a mesa.

CONTROLLING EROSION

The force that shapes valleys and coastlines is certainly enough to destroy hill slopes, often with disastrous consequences for nearby residents. Such has been the case in California, where, during the 1990s, areas were dealt a powerful one-two punch of drought followed by rain. The drought killed off much of the vegetation that

might have held the hillsides, and when rains came, they brought about mass wasting in the form of mudflows and landslides.

Over the surface of the planet, the average rate of erosion is about 1 in. (2.2 cm) in a thousand years. This is the *average,* however, meaning that in some places the rate is much, much higher, and in others it is greatly lower. The rate of erosion depends on several factors, including climate, the nature of the materials, the slope and angle of repose, and the role of plant and animal life in the local environment.

Whereas many types of plants help prevent erosion, the wrong types of planting can be detrimental. The dangers of improper land usage for crops and livestock are illustrated by the Dust Bowl experience, which highlights the fact that the organism most responsible for erosion is humanity itself. On the other hand, people also can protect against erosion by planting vegetation that holds the soil, by carefully managing and controlling land usage, and by lessening slope angle in places where gravity tends to erode the soil.

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MASS WASTING

CONCEPT

The term mass wasting (sometimes called mass movement) encompasses a broad array of processes whereby earth material is transported down a slope by the force of gravity. It is related closely to weathering, which is the breakdown of minerals or rocks at or near Earth's surface through physical, chemical, or biological processes, and to erosion, the transport of material through a variety of agents, most of them flowing media, such as air or water. Varieties of mass wasting are classified according to the speed and force of the process, from extremely slow creep to very rapid, dramatic slide or fall. Examples of rapid mass wasting include landslides and avalanches, which can be the cause of widespread death and destruction when they occur in populated areas.

HOW IT WORKS

Moving Earth and Rocks

In discussing mass wasting, the area of principal concern is Earth's surface rather than its interior. Thus, mass wasting is related most closely to the realm of geomorphology, a branch of physical geology concerned with the study of landforms, with the forces and processes that have shaped them, and with the description and classification of various physical features on Earth. Though plate tectonics (which involves the movement of giant plates beneath the earth's surface) can influence mass wasting, plate tectonics entails interior processes that humans usually witness only indirectly, by seeing their effects. Mass wasting, on the other hand, often can be observed directly, particularly in its more rapid forms, such as rock fall.

There are three general processes whereby a piece of earth material can be moved from a high outcropping to the sea: weathering, mass wasting, or erosion. If mechanical, biological, or chemical processes act on the material, dislodging it from a larger sample of material (e.g., separating a rock from a boulder), it is an example of weathering, which is discussed later in this essay. Supposing that a rock has been broken apart by weathering, it may be moved further by mass-wasting processes, such as creep or fall. Pieces of rock swept away by a river in a valley below the outcropping and small bits of rock worn away by high winds are examples of erosion. Erosion and weathering are examined in separate essays within this book.

As for the relationships between erosion, weathering, and mass wasting, the lines are not clearly drawn. Some authors treat weathering and mass wasting as varieties of erosion, and some apply a strict definition of erosion as resulting only from flowing media. (In the physical sciences, fluid means anything that flows, not just liquids.) Weathering, mass wasting, and erosion also can be viewed as stages in a process, as described in the preceding paragraph. This broad array of approaches, while perhaps confusing, only serves to illustrate the fact that the earth sciences are relatively young compared with such ancient disciplines as astronomy and biology. Not all definitions in the earth sciences are, as it were, "written in stone."

Weathering

A mineral is a substance that occurs naturally, is usually inorganic, and typically has a crystalline structure. The term *organic* does not necessarily

mean "living" rather, it refers to all carbon-containing compounds other than oxides, such as carbon dioxide, and carbonates, which are often found in Earth's rocks. A crystalline solid is one in which the constituent parts have a simple and definite geometric arrangement repeated in all directions.

Rocks, scientifically speaking, are simply aggregates or combinations of minerals or organic material or both, and weathering is the process whereby rocks and minerals are broken down into simpler materials. Weathering is the mechanism through which soil is formed, and therefore it is a geomorphologic process essential to the sustenance of life on Earth. There are three varieties of weathering: physical or mechanical, chemical, and biological.

THE THREE TYPES OF WEATHERING. Physical or mechanical weathering involves such factors as gravity, friction, temperature, and moisture. Gravity, for instance, may cause a rock to drop from a height, such that it falls to the ground and breaks into pieces. If wind-borne sand blows constantly across a rock surface, the friction will have the effect of sandpaper, producing mechanical weathering. In addition, changes in temperature and moisture will cause expansion and contraction of materials, bringing about sometimes dramatic changes in their physical structure.

Chemical weathering not only is a separate variety of weathering but also is regarded as a second stage, one that follows physical weathering. Whereas physical changes are typically external, chemical changes affect the molecular structure of a substance, bringing about a rearrangement in the ways that atoms are bonded. Important processes that play a part in chemical weathering include acid reactions, hydrolysis (a reaction with water that results in the separation of a compound to form a new substance or substances), and oxidation. The latter can be defined as any chemical reaction in which oxygen is added to or hydrogen is removed from a substance.

An example of biological weathering occurs when a plant grows from a crevice in a rock. As the plant grows, it gradually forces the sides of the crevice apart even further, and it ultimately may tear the rock apart. Among the most notable agents of biological weathering are algae and fungi, which may be combined in a mutually beneficial organism called a lichen. (Reindeer moss is an example of a lichen.) Through a combination of physical and chemical processes, organisms ranging from lichen to large animals can wear away rock gradually.

Properties of Unconsolidated Material

Regolith is a general term that describes a layer of weathered material that rests atop bedrock. It is unconsolidated, meaning that it is in pieces, like gravel, though much less uniform in size. Sand and soil, including soil mixed with loose rocks, are examples of regolith.

Every variety of unconsolidated material has its own angle of repose, or the maximum angle at which it can remain standing. Everyone who has ever attempted to build a sand castle at the beach has experienced angle of repose firsthand, perhaps without knowing it. Imagine that you are trying to build a sand castle with a steep roof. Dry sand would not be good for this purpose, because it is loose and has a tendency to flow easily. Much better would be moist sand, which can be shaped into a sharper angle, meaning that it has a higher angle of repose.

A certain amount of water gives sand surface tension, the same property that causes water to bead up on a table rather than lying flat. If too much water is added to the sand, however, the sand becomes saturated and will flow, a process called lateral spreading. Thus, to a point, the addition of water increases the angle of repose for sand, which is only about 34° when the sand is dry. (This is the angle of repose for sand in an hourglass.) On the other hand, piles of rocks may have an angle of repose as high as 45°. In practice, most aggregates of materials in nature have slopes less than their angle of repose, owing to the influence of wind and other erosive forces.

Types of Mass Wasting

As noted earlier, there is some disagreement among writers in the geologic sciences regarding the types of mass wasting. Indeed, even the term mass wasting is not universal, since some writers refer to it as mass movement. Others do not even treat the subject as a category unto itself, preferring instead to address related concepts, such as weathering and erosion, as well as instances of mass wasting, such as avalanches and landslides.



An avalanche on Mount McKinley in Alaska. *(© W. Bacon/Photo Researchers. Reproduced by permission.)*

For this reason, the classification of mass-wasting processes presented here is by no means universal and instead represents a composite of several schools of thought. Generally speaking, geologists and geomorphologists classify processes of mass wasting according to the rapidity with which they occur. Most sources recognize at least three types of mass wasting: flow, slide, and fall. Some sources include slump among the categories of relatively rapid mass-wasting process, as opposed to the slower, less dramatic (but ultimately more important) process known as creep. Some writers classify uplift and subsidence with mass wasting; however, in this book, uplift and subsidence are treated separately, in the Geomorphology essay.

REAL-LIFE APPLICATIONS

Creep

Creep is the slow downward movement of regolith as a result of gravitational force. Before the initiation of the creeping process, the regolith is in what physicists call a condition of unstable equilibrium: it remains in place, yet a relatively small disturbance would be enough to dislodge



A mudflow caused by heavy winter rains brings down the hillside under homes in Millbrae, California. *(AP/Wide World Photos. Reproduced by permission.)*

it. Though it is slow, creep can produce some of the most dramatic results over time. It can curve tree trunks at the base, break or overturn retaining walls, and cause objects from fence posts to utility poles to tombstones to be overturned.

Changes in temperature or moisture are among the leading factors that result in the disturbance of regolith. A change in either can cause material to expand or contract, and freezing or thawing may be enough to shake regolith from its position of unstable equilibrium. In fact, some geomorphologists cite a distinct mass-wasting process, known as solifluction, that occurs in the active layer of permafrost, which thaws in the summertime. Water also can provide lubrication or additional weight that assists the material in moving. One of the only causes of creep not associated with changes in temperature or moisture is the burrowing of small animals.

Slump and Slide

Slump occurs when a mass of regolith slides over or creates a concave surface (one shaped like the inside of a bowl). The result is the formation of a small, crescent-shaped cliff, known as a scarp, at the upper end—rather like the crest of a wave. Soil flow takes place at the bottom end of the slump. One is likely to see slumps in any place where forces, whether man-made or natural, have graded material to a slope too steep for its angle of repose. This may happen along an interstate highway, where a road crew has cut the slope too sharply, or on a riverbank, where natural erosion has done its work.

Often, slump is classified as a variety of slide, in which material moves downhill in a fairly coherent mass (i.e., more or less in a section or group) along a flat or planar surface. These movements sometimes are called rock slides, debris slides, or, in common parlance, landslides. Among the most destructive types of mass wasting, they may be set in motion by earthquakes, which are caused by plate tectonic processes, or by hydrologic agents (i.e., excessive rain or melting snow and ice).

Flow

When a less uniform, or more chaotic, mass of material moves rapidly downslope, it is called flow. Flow is divided into categories, depending on the amounts of water involved: granular flow (0-20% water) and slurry flow (20-40% water). Creep and solifluction often are classified as very slow forms of granular and slurry flow, respectively. In order of relative speed, these categories are as follows:

Granular Flow (0-20% Water)

- Slowest: Creep
- Slower: Earth flow
- Faster: Grain flow
- Fastest: Debris avalanche

Slurry Flow (20-40% Water)

- Slow: Solifluction
- Medium: Debris flow
- Fast: Mudflow

Earth flow moves at a rate anywhere from 3.3 ft. (1 m) per year to 330 ft. (100 m) per hour. Grain flow can be nearly 60 mi. (100 km) per hour, and debris avalanche may achieve speeds of 250 mi. (400 km) per hour, making it extremely dangerous. Among types of slurry flow, debris flow is roughly analogous to earth flow, falling into a range from about 4 in. (10 cm) per year to 0.6 mi. (1 km) per hour. Mudflow is slightly faster than grain flow. If the water content is more than 40%, a slurry flow is considered a stream.

Earth flows involve fine-grained materials, such as clay or silt, and typically occur in humid areas after heavy rains or the melting of snow. Debris flows usually result from heavy rains as well and may start with slumps before flowing downhill, forming lobes with a surface broken by ridges and furrows. Grain flows can be caused by a small disturbance, which forces the dry, unconsolidated material rapidly downslope. Debris avalanches are commonly the result of earthquakes or volcanic eruptions.

Seismic disturbances or volcanic activity may cause the collapse of a mountain slope, sending debris avalanches moving swiftly even along the gentler slopes of the mountainside. Likewise, mudflows may be the result of volcanic activity, in which case they are known as lahars. In some situations, the material in a lahar is extremely hot. Mudflows tend to be highly fluid mixtures of sediment (material deposited at or near Earth's surface from a number of sources, most notably preexisting rock) and water and typically flow along valley floors.

Fall

Most other forms of mass wasting entail movement along slopes that are considerably less than 90°, whereas fall takes place at angles almost perpendicular to the ground. Anyone who has driven through a wide mountain area, with steep cliffs on either side, has seen signs that say "Watch for Falling Rock." These warnings, which appear regularly on the drive through the Rockies in Colorado or on highways across the Blue Ridge and Great Smoky mountains in the southern United States, indicate the threat of rock fall.

The mechanism behind rock fall is simple enough. When a rock at the top of a slope is in unstable equilibrium, it can be dislodged such that it either falls directly downward or bounces and rolls. Usually, the bottom of the slope or cliff contains accumulated talus, or fallen rock material. Freezing and thawing as well as the growth of plant roots may cause fall. The latter is not limited to rock fall: debris fall, which is closely related, includes soil, vegetation, and regolith as well as rocks.

Mass Wasting and Natural Disasters

Among the most dramatic and well-known varieties of mass wasting are avalanches, a variety of flow, and landslides, which (as their name suggests) are a type of slide. These can result, and have resulted, in enormous loss of life and property. Some notable modern occurrences of mass wasting, and the type of movement involved, are listed below. With each incident, the approximate number of fatalities is shown in parentheses.

- *China, 1920:* Landslide caused by an earthquake (200,000)
- *Peru, 1970:* Debris avalanche related to an earthquake (70,000)
- *Colombia, 1985:* Mudflow related to a volcanic eruption (23,000)
- *Soviet Union, 1949:* Landslide caused by an earthquake (12,000–20,000)
- *Italy and Austria, 1916:* Landslide (10,000)
- *Peru, 1962:* Landslide (4,000–5,000)
- *Italy, 1963:* Landslide (2,000)
- *Japan, 1945:* Landslide caused by a flood (1,200)
- *Ecuador, 1987:* Landslide related to an earthquake (1,000)
- *Austria, 1954:* Landslide (200)

The Role of Plate Tectonics

Note how many times an instance of mass wasting was either caused by or "related to" (meaning that geologists could not establish a full causal relationship) volcanic or seismic activity. Both, in

KEY TERMS

ANGLE OF REPOSE: The maximum slope at which a relatively large sample of unconsolidated material can remain standing. Often, the addition of water increases the angle of repose, up to the point at which the material becomes saturated.

AVALANCHE: See *flow.*

CREEP: A form of mass wasting involving the slow downward movement of regolith as a result of gravitational force.

EROSION: The movement of soil and rock due to forces produced by water, wind, glaciers, gravity, and other influences. In most cases, a fluid medium, such as air or water, plays a part.

FALL: A form of mass wasting in which rock or debris moves downward along extremely steep angles.

FLOW: A form of mass wasting in which a body of material that is not uniform moves rapidly downslope. Flow is divided into categories, depending on the amounts of water involved: granular flow (0-20% water) and slurry flow (20-40% water). An avalanche is an example of flow and may involve either rock (granular) or snow (slurry).

FLUID: In the physical sciences, the term fluid refers to any substance that flows and therefore has no definite shape—that is, both liquids and gases. In the earth sciences, occasionally substances that appear to be solid, for example, ice in glaciers, are, in fact, flowing slowly.

GEOMORPHOLOGY: An area of physical geology concerned with the study of landforms, with the forces and processes that have shaped them, and with the description and classification of various physical features on Earth.

LANDSLIDE: See *slide.*

LITHOSPHERE: The upper layer of Earth's interior, including the crust and the brittle portion at the top of the mantle.

turn, are the result of plate movement in most instances, and thus it is not surprising that several of the locales noted here are either at plate margins or in mountainous regions where plate tectonic and other processes are at work. (For more on this subject, see the entries Plate Tectonics and Mountains.)

To set mass wasting into motion, it is necessary to have a steep slope and some type of force to remove material from its position of unstable equilibrium. Plate tectonic processes provide both. Not only does an earthquake, for instance, jar rocks loose from the upper portion of a slope, but the movement of plates also helps create steep slopes, for example, the collision of the Indo-Australian and Eurasian belts that produced the Himalayas.

Some of the most vigorous plate tectonic activity occurs underwater, and, likewise, there are remarkable manifestations of mass wasting beneath the seas. Off Moss Landing, a research facility that serves a consortium of state universities in northern California, is an underwater canyon more than 0.6 mi. (1 km) deep. At one time, Monterey Canyon was thought to be the result of erosion by a river flowing into the ocean; however, today it is believed to be the result of underwater mass wasting.

Detecting and Preventing Mass Wasting

The dramatic instances of mass wasting discussed here hardly require any effort at detection. Their effect is obvious and, to those unfortunate enough

KEY TERMS

MASS WASTING: The transfer of earth material down slopes by processes that include creep, slump, slide, flow, and fall. Also known as *mass movement.*

PLATE MARGINS: Boundaries between plates.

PLATE TECTONICS: The name both of a theory and of a specialization of tectonics. As an area of study, plate tectonics deals with the large features of the lithosphere and the forces that shape them. As a theory, it explains the processes that have shaped Earth in terms of plates and their movement.

PLATES: Large, movable segments of the lithosphere.

REGOLITH: A general term describing a layer of weathered material that rests atop bedrock.

SEDIMENT: Material deposited at or near Earth's surface from a number of sources, most notably preexisting rock.

SLIDE: A variety of mass wasting in which material moves downhill in a fairly coherent mass (i.e., more or less in a section or group) along a flat or planar surface.

SLUMP: A form of mass wasting that occurs when a mass of regolith slides over or creates a concave surface (one shaped like the inside of a bowl).

SURFACE TENSION: An attractive force exerted by molecules in the interior of a liquid on molecules at the exterior. This force draws the material inward such that it occupies less than its maximum horizontal area. The surface tension of water is high, causing it to bead on most surfaces.

UNSTABLE EQUILIBRIUM: A situation in which an object remains in place, yet a relatively small disturbance would be enough to dislodge it.

WEATHERING: The breakdown of rocks and minerals at or near the surface of Earth due to physical, chemical, or biological processes.

to be nearby, inescapable. Other types of mass wasting occur so slowly that they do not invite immediate detection. This can be unfortunate, because in some cases slow mass wasting is a harbinger of much more rapid movements to follow.

A dwelling atop a hill is subject to enormous gravitational force, and the more massive the dwelling, the greater the pull of gravity. (Weight is, after all, nothing but gravitational force.) If a homeowner adds a swimming pool or other items that contribute to the weight of the dwelling, it only increases the chances that it may experience mass wasting. Heavy rains can bring so much water that it saturates the soil, reducing its surface tension and causing it to slide—as occurred, for instance, in the area around Malibu, California, during the late 1990s.

The California mud slides and landslides are a dramatic example of mass wasting, but more often than not mass wasting takes the form of creep, which is detectable only over a matter of years. When creep occurs, the upper layer of soil moves, while the layer below remains stationary. One way to keep the upper layer in place is to plant vegetation that will put down roots deep enough to hold the soil.

This may create unintended consequences. During the 1930s, New Deal officials imported kudzu plants from China, intending to protect the hillsides of the American South from creep and erosion. The kudzu protected the slopes, but as it turned out, this voracious plant had a tendency to creep as well. Before communities began taking steps to eradicate it, or at least push

it back, in the 1970s, kudzu seemingly threatened to cover the entire southern United States.

To prevent some of the more dramatic varieties of mass wasting, such as landslides in a residential area, a homeowner or group of homeowners may commission an engineer's study. The engineer can test the material of the slope, measure the stresses acting on it, and perform other calculations to predict the likelihood that a slope will succumb to a given amount of force. For this reason, zoning laws in areas with steep slopes are typically strict. These laws are geared toward preventing homeowners and builders from erecting structures likely to create a threat of mass wasting in a period of heavy rains.

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SEDIMENTOLOGY AND SOIL SCIENCE

SEDIMENT AND SEDIMENTATION

SOIL

SOIL CONSERVATION

SEDIMENT AND SEDIMENTATION

CONCEPT

The materials that make up Earth are each products of complex cycles and interactions, as a study of sediment and sedimentation shows. Sediment is unconsolidated material deposited at or near Earth's surface from a number of sources, most notably preexisting rock. There are three kinds of sediment: chemical, organic, and rock, or clastic sediment. Weathering removes this material from its source, while erosion and mass wasting push it along to a place where it is deposited. After deposition, the material may become a permanent part of its environment, or it may continue to undergo a series of cycles in which it experiences ongoing transformation.

HOW IT WORKS

Transporting Sediment

There are three types of sediment: rocks, or clastic sediment; mineral deposits, or chemical sediment; and organic sediment, composed primarily of organic material. (In this context, the term *organic* refers to formerly living things and parts or products of living things; however, as discussed in Minerals, the term actually has a much broader meaning.) There are also three general processes involved in the transport of sediment from higher altitudes to lower ones, where they eventually are deposited: weathering, mass wasting, and erosion.

The lines between these three processes are not always clearly drawn, but, in general, the following guidelines apply. When various processes act on the material, causing it to be dislodged from a larger sample (for example, separating a rock from a boulder), this is an example of weathering. Assuming that a rock has been broken apart by weathering, it may be moved farther by mass-wasting processes, such as creep or fall, for which gravity is the driving factor. If the pieces of rock are swept away by a river, high winds, or a glacier (all of which are flowing media), this is an example of erosion.

WEATHERING. Weathering is divided further into three different types: physical, chemical, and biological. Physical or mechanical weathering takes place as a result of such factors as gravity, friction, temperature, and moisture. Gravity may cause a rock to roll down a hillside, breaking to pieces at the bottom; friction from particles of matter borne by the wind may wear down a rock surface; and changes in temperature and moisture can cause expansion and contraction of materials.

Whereas physical weathering attacks the rock as a whole, chemical weathering involves the breakdown of the minerals or organic materials that make up the rock. Chemical breakdown may lead to the dissolution of the materials in the rock, which then are washed away by water or wind or both, or it may be merely a matter of breaking the materials down into simpler compounds.

Biological weathering is not so much a third type of weathering as it is a manifestation of chemical and physical breakdown caused by living organisms. Suppose, for instance, that a plant grows within a crack in a rock. Over time, the plant will influence physical weathering through its moisture and the steady force of its growth pushing at the walls of the fissure in which it is rooted. At the same time, its specific chemical



Sediment can be transported by weathering, erosion, and mass wasting. Here a winter storm has caused coastal erosion of a beach. *(© Rafael Macia/Photo Researchers. Reproduced by permission.)*

properties likely will induce decomposition of the rock.

MASS WASTING. Mass wasting, sometimes known as mass movement, comprises a number of types of movement of earth material, all of them driven by gravity. Creep is the slow downward drift of regolith (unconsolidated material produced by weathering), while slump occurs when a mass of regolith slides over, or creates, a concave surface—that is, one shaped like the inside of a bowl. Slump sometimes is classified as a variety of slide, in which material moves downhill in a fairly coherent mass along a flat or planar surface. Such movements, sometimes called rock slides, debris slides, or landslides, are among the most destructive types of mass wasting.

When a less uniform, or more chaotic, mass of material moves rapidly down a slope, it is called flow. Flow is divided into categories, depending on the specific amounts of water: granular flows (0–20% water) and slurry flows (20–40% water), the fastest varieties of which are debris avalanche and mudflow, respectively. Mudflows can be more than 60 mi. (100 km) per hour, while debris avalanches may achieve speeds of 250 mi. (400 km) per hour.

Even these high-speed varieties of mass wasting entail movement along slopes that are considerably less than 90°, whereas a final variety of mass wasting, that is, fall, takes place at angles almost perpendicular to the ground. Typically the bottom of a slope or cliff contains accumulated talus, or fallen rock material. Nor is fall limited to rock fall: debris fall, which is closely related, includes soil, vegetation, and regolith as well as rocks. (For more on these subjects, see Mass Wasting.)

Erosion

Erosion typically is caused either by gravity (in which case it is generally known as mass wasting, discussed earlier) or by flowing media, such as water, wind, and even ice in glaciers. It removes sediments in one of three ways: by the direct impact of the agent (i.e., the flowing media that is discussed in the following sections); by abrasion, another physical process; or by corrosion, a chemical process.

In the case of direct impact, the wind, water, or ice removes sediment, which may or may not be loose when it is hit. On the other hand, abrasion involves the impact of solid earth materials carried by the flowing agent rather than the impact of the flowing agent itself. For example, sand borne by the wind, as discussed later, or pebbles carried by water may cause abrasion.

Corrosion is chemical and is primarily a factor only in water-driven, as opposed to wind-driven or ice-driven, erosion. Streams slowly dissolve rock, removing minerals that are carried downstream by the water.

WATER. Of the fluid substances driving erosion, liquid water is perhaps the one most readily associated in most people's minds with erosion. In addition to the erosive power of waves on the seashore, there is the force exerted by running water in creeks, streams, and rivers. As a river moves, pushing along sediment eroded from the streambeds or riverbeds, it carves out deep chasms in the bedrock beneath.

Moving bodies of water continually reshape the land, carrying soil and debris down slopes, from the source of the river to its mouth, or delta. A delta is a region formed when a river enters a larger body of water, at which point the reduction in velocity on the part of the river current leads to the widespread deposition of sediment. It is so named because its triangular shape resembles that of the Greek letter delta, Δ.

Water at the bottom of a large body, such as a pond or lake, also exerts erosive power; then there is the influence of falling rain. Assuming that the ground is not protected by vegetation, raindrops can loosen particles of soil, sending them scattering in all directions. A rain that is heavy enough may dislodge whole layers of topsoil and send them rushing away in a swiftly moving current. The land left behind may be rutted and scarred, much of its best soil lost for good.

ICE. Ice, of course, is simply another form of water, but since it is solid, its physical properties are quite different. It is a solid rather than a fluid, such as liquid water or air (the physical sciences treat gases and liquids collectively as "fluids"), yet owing to the enormous volume of ice in glaciers, these great masses are capable of flowing. Glaciers do not flow in the same way as a fluid does; instead, they are moved by gravity, and like giant bulldozers made of ice, they plow through rock, soil, and plants.

Under certain conditions a glacier may have a layer of melted water surrounding it, which greatly enhances its mobility. Even without such lubricant, however, these immense rivers of ice move steadily forward, gouging out pieces of bedrock from mountain slopes, fashioning deep valleys, removing sediment from some regions and adding it to others. In unglaciated areas, or places that have never experienced any glacial activity, sediment is formed by the weathering and decomposition of rock. On the other hand, formerly glaciated areas are distinguished by layers of till, or glacial sediment, from 200 to 1,200 ft. (61–366 m) thick.

WIND. The processes of wind erosion sometimes are called *eolian* processes, after Aeolus, the Greek god of the winds. Eolian erosion is in some ways less forceful than the erosive influence of water. Water, after all, can lift heavier and larger particles than can the winds. Wind, however, has a much greater frictional component in certain situations. This is particularly true when the wind carries sand, every grain of which is like a cutting tool.

Wind erosion, in fact, is most pronounced in precisely those places where sand abounds, in deserts and other areas that lack effective ground cover in the form of solidly rooted, prevalent vegetation. In some desert regions the bases of rocks or cliffs have been sandblasted, leaving a mushroom-shaped formation owing to the fact that the wind could not lift the fine grains of sand very high.

SEDIMENT LOAD

Eroded particles become part of what is called the sediment load transported by the fluid medium. Sediment load falls into three categories: dissolved load, suspended load, and bed load. The amount of each type of load that a fluid medium is capable of carrying depends on the density of the fluid medium itself: in other words, wind can carry the least of each and ice the most.

The wind does not carry any dissolved load, since solid particles (unlike gases) cannot be dissolved in air. Ice or water, on the other hand, is able to dissolve materials, which become invisible within them. Typically, about 90% of the dissolved load in a river is accounted for by five different ions, or atoms that carry a net electric charge: the anions (negative ions) chloride, sulfate, and bicarbonate and the cations (positive ions) of sodium and calcium.

Suspended load is sediment that is suspended, or floating, in the erosive medium. In this instance, wind is just as capable as water or ice of suspending particles of the sediment load, which are likely to color the medium that carries them. Hence, water or wind carrying suspended parti-

cles is usually murky. The thicker the medium, the larger the particles it is capable of suspending. In other words, ice can suspend extremely large pieces of sediment, whereas water can suspend much more modest ones. Wind can suspend only tiny particles.

Then there is bed load, large sediment that never becomes suspended but rather is almost always in contact with the substrate or bottom, whether "the bottom" is a streambed or the ground itself. Instead of being lifted up by the medium, bed load is nudged along, rolling, skipping, and sliding as it makes its way over the substrate. Once again, the density of the medium itself has a direct relationship to the size of the bed load it is capable of carrying. Wind rarely transports bed load thicker than fine sand, and water usually moves only pebbles, though under flood conditions it can transport boulders. As with suspended load, glaciers can transport virtually any size of bed load.

Sediment Sizes and Shapes

Geologists and sedimentologists use certain terms to indicate sizes of the individual particles in sediment. Many of these terms are familiar to us from daily life, but whereas people typically use them in a rather vague way, within the realm of sedimentology they have very specific meanings. Listed below are the various sizes of rock, each with measurements or measurement ranges for the rock's diameter:

- Clay: Smaller than 0.00015 in. (0.004 mm)
- Silt: 0.00015 in. (0.004 mm) to 0.0025 in. (0.0625 mm)
- Sand: 0.0025 in. (0.0625 mm) to 0.08 in. (2 mm)
- Pebble: 0.08 in. (2 mm) to 2.5 in. (64 mm)
- Cobble: 2.5 in. (64 mm) to 10 in. (256 mm)
- Boulder: Larger than 10 in. (256 mm).

This listing is known as the Udden–Wentworth scale, which was developed in 1898 by J.A. Udden (1859–1932), an American sedimentary petrologist (a scientist who studies rocks). In 1922 the British sedimentary petrologist C. K. Wentworth) expanded Udden's scale, adapting the definitions of various particle sizes to fit more closely with the actual usage and experience of researchers in the field. The scale uses modifiers to pinpoint the relative sizes of particles. In ascending order of size, these sizes are very fine, fine, medium, coarse, and very coarse.

Real-Life Applications

Sediments and Dust Bowls

Sediment makes possible the formation of soil, which of course is essential for growing crops. Therefore it is a serious matter indeed when wind and other forces of erosion remove sediment, creating dust-bowl conditions. The term "Dust Bowl," with capital letters, refers to the situation that struck the United States Great Plains states during the 1930s, devastating farms and leaving thousands of families without home or livelihood. (See Erosion for much more about the Dust Bowl.)

During the late 1990s, some environmentalists became concerned that farming practices in the western United States were eroding sediment, putting in place the possibility of a return to the conditions that created the Dust Bowl. However, in August 1999, the respected journal *Science* reported studies showing that sediment in farmlands was not eroding at anything like the rate that had been feared. Soil scientist Stanley Trimble at the University of California, Los Angeles, studied Coon Creek, Wisconsin, and its tributaries, a watershed for which 140 years' worth of erosion data were available. As Trimble discovered, the rate of sediment erosion in the area had dramatically decreased since the 1930s, and was now at 6% of the rate during the Dust Bowl years.

Some studies from the 1970s onward had indicated that farming techniques, designed to improve the crop output from the soil, had created a situation in which sediment was being washed away at alarming rates. However, if such sediment removal were actually taking place, there would have to be some evidence—if nothing more, the sediment that had been washed away would have had to go somewhere. Instead, as Trimble reported, "We found that much of the sediment in Coon Creek doesn't move very far, and that it moves in complex ways." The sediment, as he went on to explain, was moving within the Coon Creek basin, but the amount that actually made it to the Mississippi River (which could be counted as true erosion, since it was removing sediment from the area) had stayed essentially the same for the past 140 years.



Sedimentary structures remaining in a dried river bed. Clay soils crack as they lose moisture and contract when trapped water evaporates as the result of drought. *(© B. Edmaier/Photo Researchers. Reproduced by permission.)*

Deposition and Depositional Environments

Eventually everything in motion—including sediment—comes to rest somewhere. A piece of sediment traveling on a stream of water may stop hundreds of times, but there comes a point when it comes to a complete stop. This process of coming to rest is known as deposition, which may be of two types, mechanical or chemical. The first of these affects clastic and organic sediment, while the second applies (fittingly enough) to chemical sediment.

In mechanical deposition, particles are deposited in order of their relative size, the largest pieces of bed load coming to a stop first. These large pieces are followed by medium-size pieces and so on until both bed load and suspended load have been deposited. If the sediment has come to a full stop, as, for instance, in a stagnant pool of water, even the finest clay suspended in the water eventually will be deposited as well.

Unlike mechanical deposition, chemical deposition is not the result of a decrease in the velocity of the flow; rather, it comes about as a result of chemical precipitation, when a solid particle crystallizes from a fluid medium. This often happens in a saltwater environment, where waters may become overloaded with salt and other minerals. In such a situation, the water is

unable to maintain the minerals in a dissolved state (i.e., in solution) and precipitates part of its content in the form of solids.

DEPOSITIONAL ENVIRONMENTS. The matter of sediment deposition in water is particularly important where reservoirs are concerned, since in that case the water is to be used for drinking, cooking, bathing, and other purposes by humans. One of the biggest problems for the maintenance of clean reservoirs is the transport of sediment from agricultural areas, in which the soil is likely to contain pesticides and other chemicals, including the phosphorus found in fertilizer. A number of factors, including precipitation, topography, and land use, affect the rate at which sediment is deposited in reservoirs.

The area in which sediment is deposited is known as its depositional environment, of which there are three basic varieties: terrestrial, marginal marine, and marine. These are, respectively, environments on land (and in landlocked waterways, such as creeks or lakes), along coasts, and in the open ocean. A depositional environment may be a large-scale one, known as a regional environment, or it may be a smaller subenvironment, of which there may be hundreds within a given regional environment.

SEDIMENTARY STRUCTURES. There are many characteristic physical formations, called sedimentary structures, that sediment forms after it has reached a particular depositional environment. These formations include bedding planes and beds, channels, cross-beds, ripples, and mud cracks. A bed is a layer, or stratum, of sediment, and bedding planes are surfaces that separate beds. The bedding plane indicates an interruption in the regular order of deposition. (These are concepts that also apply to the field of stratigraphy. For more on that subject, see the essay Stratigraphy.)

Channels are simply depressions in a bed that reflect the larger elongated depression made by a river as it flows along its course. Cross-beds are portions of sediment that are at an angle to the beds above and below them, as a result of the action of wind and water currents—for example, in a flowing stream. As for ripples, they are small sandbar-like protuberances that form perpendicular to the direction of water flow. At the beach, if you wade out into the water and look down at your feet, you are likely to see ripples perpendicular to the direction of the waves. Finally, mud cracks are the sedimentary structures that remain when water trapped in a muddy pool evaporates. The clay, formerly at the bottom of the pool, begins to lose its moisture, and as it does, it cracks.

The Impact of Sediment

It is estimated that the world's rivers carry as much as 24 million tons (21,772,800 metric tons) of sediment to the oceans each year. There is also the sediment carried by wind, glaciers, and gravity. Where is it all going? The answer depends on the type of sediment. Clastic and organic sediment may wind up in a depositional environment and experience compaction and cementation in the process of becoming sedimentary rock. (For more on sedimentary rock, see Rocks.)

On the other hand, clastic and organic particles may be buried, but before becoming lithified (turned to rock), they once again may be exposed to wind and other forces of nature, in which case they go through the entire cycle again: weathering, erosion, transport, deposition, and burial. This cycle may repeat many times before the sediment finally winds up in a permanent depositional environment. In the latter case, particles of clastic and organic sediment ultimately may become part of the soil, which is discussed elsewhere in this book (See Soil).

A chemical sediment also may become part of the soil, or it may take part in one or more biogeochemical cycles (also discussed elsewhere; see Biogeochemical Cycles). These chemicals may wind up as water in underground reservoirs, as ice at Earth's poles, as gases in the atmosphere, as elements or compounds in living organisms, or as parts of rocks. Indeed, all three types of sediment—clastic, chemical, and organic—are part of what is known as the rock cycle, whereby rocks experience endlessly repeating phases of destruction and renewal. (See Rocks for more details.)

Sedimentary Mineral Deposits

Among the most interesting aspects of sediment are the mineral deposits it contains—deposits that may, in the case of placer gold, be of significant value. A placer deposit is a concentration of heavy minerals left behind by the effect of gravity on moving particles, and since gold is the densest of all metals other than uranium (which

KEY TERMS

BED LOAD: Sediment that is capable of being transported by an erosive medium (wind, water, or air) but only under conditions in which it remains in nearly constant contact with the substrate or bottom (e.g., a streambed or the ground). Bed load, along with dissolved load and suspended load, is one of three types of sediment load.

COMPOUND: A substance made up of atoms of more than one element chemically bonded to one another.

CONSOLIDATION: A process whereby materials become compacted, or experience an increase in density. This takes place through a number of processes, including recrystallization and cementation.

DEPOSITION: The process whereby sediment is laid down on the Earth's surface.

DIAGENESIS: A term referring to all the changes experienced by a sediment sample under conditions of low temperature and low pressure following deposition.

DISSOLVED LOAD: Sediment load that is absorbed completely by the erosive medium (either water or ice) that carries it. Dissolved load is one of three types of sediment load, the others being suspended load and bed load.

EROSION: The movement of soil and rock due to forces produced by water, wind, glaciers, gravity, and other influences. In most cases, a fluid medium, such as air or water, is involved.

FLUID: In the physical sciences, the term fluid refers to any substance that flows and therefore has no definite shape—that is, both liquids and gases. Occasionally, substances that appear to be solid (for example, ice in glaciers), in fact, are flowing slowly; therefore, within the earth sciences, ice often is treated as another fluid medium.

ION: An atom or group of atoms that has lost or gained one or more electrons and thus has a net electric charge. Positively charged ions are called *cations,* and negatively charged ones are called *anions.*

MASS WASTING: The transfer of earth material down slopes by processes that include creep, slump, slide, flow, and fall. Also known as *mass movement.*

MINERAL: A naturally occurring, typically inorganic substance with a specific chemical composition and a crystalline structure.

ORGANIC: At one time, chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals) and oxides, such as carbon dioxide.

PRECIPITATION: In the context of chemistry, precipitation refers to the formation of a solid from a liquid.

REGOLITH: A general term describing a layer of weathered material that rests atop bedrock.

ROCK: An aggregate of minerals or organic matter, which may be consolidated or unconsolidated.

KEY TERMS CONTINUED

SEDIMENT: Material deposited at or near Earth's surface from a number of sources, most notably preexisting rock. There are three types of sediment: rocks, or clastic sediment; mineral deposits, or chemical sediment; and organic sediment, composed primarily of organic material.

SEDIMENTARY ROCK: One of the three major types of rock, along with igneous and metamorphic rock. Sedimentary rock usually is formed by the deposition, compaction, and cementation of rock that has experienced weathering. It also may be formed as a result of chemical precipitation.

SEDIMENTATION: The process of erosion, transport, and deposition undergone by sediment.

SEDIMENT LOAD: A term for the particles transported by a flowing medium of erosion (wind, water, or ice). The types of sediment load are dissolved load, suspended load, and bed load.

SEDIMENTOLOGY: The study and interpretation of sediments, including sedimentary processes and formations.

SUSPENDED LOAD: Sediment that is suspended, or floating, in the erosive medium (wind, water, or ice). Suspended load is one of three types of sediment load, along with dissolved load and bed load.

TILL: A general term for the sediments left by glaciers that lack any intervening layer of melted ice.

UNCONSOLIDATED ROCK: Rock that appears in the form of loose particles, such as sand.

WEATHERING: The breakdown of rocks and minerals at or near the surface of Earth due to physical, chemical, or biological processes.

is even more rare), it is among the most notable of placer deposits.

Of course, the fact that gold is valuable has done little to hurt, and a great deal to help, human fascination with placer gold deposits. Placer gold played a major role from the beginning of the famous California Gold Rush (1848–49), which commenced with discovery of a placer deposit by prospector James Marshall on January 24, 1848, along the American River near the town of Coloma. This discovery not only triggered a vast gold rush, as prospectors came from all over the United States in search of gold, but it also proved a major factor in the settlement of the West. Most of the miners who went to the West failed to make a fortune, of course, but instead they found something much better than gold: a gorgeous, fertile land like few places in the United States—California, a place that today holds every bit as much allure for many Americans as it did in 1848.

Despite the attention it naturally attracts, gold is far from the only placer mineral. Other placer minerals, all with a high specific gravity (density in comparison to that of water), include platinum, magnetite, chromite, native copper, zircon, and various gemstones. Nor are placer minerals found only in streams and other flowing bodies of water; wave action and shore currents can leave behind what are called beach placers. Among the notable beach placers in the world are gold deposits near Nome, Alaska, as well as zircon in Brazil and Australia, and marine gravel near Namaqualand, South Africa, which contains diamond particles.

An entirely different process can result in the formation of evaporites, minerals that include carbonates, gypsum, halites, and magnesium and potassium salts. (These specific mineral types are

discussed in Minerals.) Formed when the evaporation of water leaves behind ionic, or electrically charged, chemical compounds, evaporites sometimes undergo physical processes similar to those of clastic sediment. They may even have graded bedding, meaning that the heavier materials fall to the bottom. In addition to their usefulness in industry and commerce (e.g., the use of gypsum in sheetrock for building), physical and chemical aspects of evaporites also provide scientists with considerable information regarding the past climate of an area.

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SOIL

CONCEPT

If there is anything on Earth that seems simple and ordinary, it is the soil beneath our feet. Other than farmers, people hardly think of it except when tending to their lawns, and even when we do turn our attention to the soil, we tend to view it as little more than a place where grass grows and earthworms crawl. Yet the soil is a complex mixture of minerals and organic material, built up over billions of years, and without it, life on this planet would be impossible. It is home to a vast array of species that continually process it, enriching it as they do. Nor are all soils the same; in fact, there are a great variety of soil environments and a great deal of difference between the soil at the surface and that which lies further down, closer to the bedrock.

HOW IT WORKS

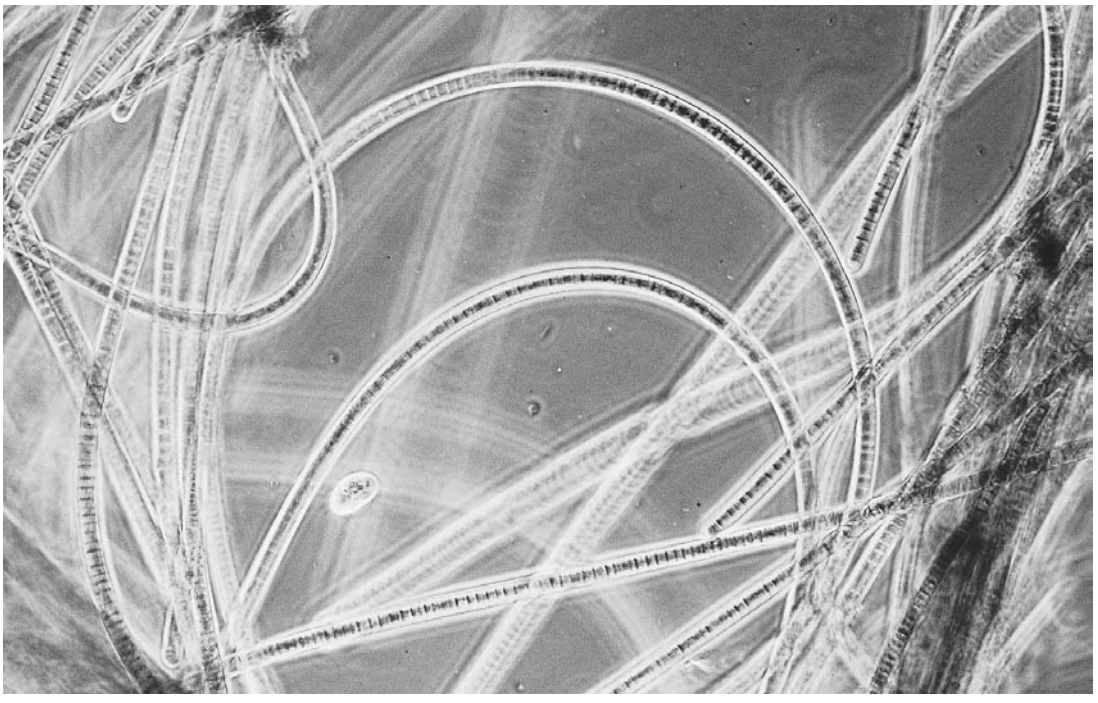
The Beginnings of Soil Formation

It has taken billions of years to yield the soil as we know it now. Over the course of these mind-boggling stretches of time, the chemical elements on Earth came into existence, and the uniformly rocky surface of the planet gradually gave way to deposits of softer material. This softer matter, the earliest ancestor of soil, became enriched by the presence of minerals from the rocks and, over a longer period, by decaying organic matter.

After its formation from a cloud of hot gas some 4.5 billion years ago, Earth was pelted by meteorites. These meteorites brought with them solid matter along with water, forming the basis for the oceans. There was no atmosphere as such, but by about four billion years ago, volcanic activity had ejected enough carbon dioxide and other substances into the air to form the beginnings of one. The oceans began to cool, making possible the earliest forms of life—that is, molecules of carbon-based matter that were capable of replicating themselves. (For more on these subjects, see Sun, Moon, and Earth and Geologic Time. On the relationship between carbon and life-forms, see Carbon Cycle.)

All of these conditions—Earth itself, an atmosphere, waters, and life-forms—went into the creation of soil. Soil has its origins in the rocks that now lie below Earth's surface, from which the rain washed minerals. For rain to exist, of course, it was necessary to have water on the planet, along with some form of atmosphere into which it could evaporate. Once these conditions had been established (as they were, over hundreds of millions of years) and the rains came down to cool the formerly molten rock of Earth's surface, a process of leaching began.

Leaching is the removal of soil particles that have become dissolved in water, but at that time, of course, there was no soil. There were only rocks and minerals, but these features of the geosphere, along with the chemical elements in the atmosphere and hydrosphere, were enough to set in motion the development of soil. While the atmosphere and hydrosphere supplied the falling rain, with its vital activity of leaching minerals from the rocks, the minerals themselves supplied additional chemical elements necessary to the formation of soil. (The chemical elements are discussed in several places, most notably Biogeochemical Cycles. See also Minerals and Rocks.)



Light micrograph of blue-green algae, an example of the simplest plant organisms that were the forerunners of life on the earth. Plant life was made possible by the leaching of potassium, calcium, and magnesium from rock, and, in turn, plant death lent organic matter to the ground to help form the basis for soil. *(© S. Stammers/Photo Researchers. Reproduced by permission.)*

THE FIRST PLANTS. Among the elements leached from the rock by the falling rains were potassium, calcium, and magnesium, all of which are essential for the growth of plant life. Thus, the foundation was laid for the first botanical forms, a fact that had several important consequences. First and most obviously, it helped set in motion the formation of the complex biosphere we have around us today. Not only did the simplest algae-like plants serve as forerunners for more complex varieties of plant and animal life to follow, but they also played a major role in the beginnings of an atmosphere breathable by animal life. As the plants absorbed carbon dioxide from their surroundings, there gradually evolved a process whereby the plant received carbon dioxide and, as a result of a chemical reaction, released oxygen.

In addition, plant life meant plant death, and as each plant died, it added just a bit more organic material—and with it nutrients and energy—to the ground. Notice the word ground as opposed to soil, which took a long, long time to form from the original rock and mineral material. Indeed, the processes we are describing here did not take shape over the course of centuries or millennia but over whole eons—the longest phases of geologic time, stretching for half a billion years or more (see Geologic Time). Only around the beginning of the present eon, the Phanerozoic, more than 500 million years ago, did soil as such begin to take shape.

What Is Soil?

As the soil began to form, processes of weathering, erosion, and sedimentation (see the entries Erosion and Sediment and Sedimentation) slowly added to the soil buildup. Today the soil forms a sheath over much of the solid earth; just inches deep or nonexistent in some places, it is many feet deep in others. It separates the planet's surface from its rocky interior and brings together a number of materials that contribute to and preserve life.

Though its origins lie in pulverized rock and decayed organic material, soil looks and feels like neither. Whether brown, red, or black, moist or dry, sandy or claylike, it is usually fairly uniform within a given area, a fact for which the organisms living in it can be thanked. Under the surface of the soil live bacteria, fungi, worms, insects, and

other creatures that continually churn through it and process its chemical contents.

A filter for water and a reservoir for air, soil provides a sort of stage on which the drama of an ecosystem (a community of mutually interdependent organisms) is played out. It receives rain and other forms of precipitation, which it filters through its layers, replenishing the groundwater supplies. This natural filtration system, sometimes augmented by a little human ingenuity, is amazingly efficient for leaching out harmful microorganisms and toxins at relatively low levels. (Thus, for instance, septic tank drainage systems process wastewater, with the help of soil, before returning it to the water table.)

By collecting rainwater, soil also gives the rain a place to go and thus helps prevent flooding. Water is not the only substance it stores; soil also collects air, which accounts for a large percentage of its volume. Thus, oxygen is made available to the roots of plants and to the large populations of organisms living underground. The creatures that live in the soil also die there, providing organic material that decays along with a vast collection of dead organisms from aboveground: trees and other plants as well as dead animals—including humans, whose decomposed bodies eventually become part of the soil as well.

Factors That Influence Soil

The processes that formed soil over the eons and that continue to contribute to the soil under our feet today are similar to those by which sedimentary rock is formed. Sedimentary rocks, such as shale and sandstone, have their origins in the deposition, compaction, and cementation of rock that has experienced weathering. Added to this is organic material derived from its ecosystem—for example, fossilized remains of animals.

Both sedimentary rock and soil are made up of sediment, which originates from the weathering, or breakdown, of rock. Weathered remains of rocks ultimately are transported by forces of erosion to what is known as a depositional environment, a location where they are sedimented. (See Sediment and Sedimentation for more about these processes.) The nature of the "parent material," or the rock from which the soil is derived, ranks among five key factors influencing the characteristics of soil in a given environment. The others are climate, living organisms, topography, and time.

PARENT MATERIAL, CLIMATE, AND ORGANISMS. Minerals, such as feldspars and micas, react strongly to natural acids carried by rain and other forms of water; therefore, when these minerals are present in the rock that makes up the parent material, they break apart quite easily into small fragments. On the other hand, a mineral that is harder—for example, quartz—will break into larger pieces of clastic, or rock, sediment. Thus, the parent material itself has a great deal to do with the initial grain of the sediment that will become soil, and this in turn influences such factors as the rate at which water leaches through it.

The release of chemical compounds and elements from minerals in weathering provides plants with the nutrients they need to grow, setting in motion the first of several steps whereby living organisms take root in, and ultimately contribute to, the soil. As the plant dies, it leaves behind material to feed decomposers, such as bacteria and fungi. The latter organisms play a highly significant role in the biogeochemical cycles whereby certain life-sustaining elements are circulated through the various earth systems.

In addition, still-living plants provide food to animals, which, when they die, likewise will become one with the soil. This is achieved through the process of decomposition, aided not only by decomposers but by detritivores as well. The latter, of which earthworms are a great example, are much more complex organisms than the typically single-cell decomposers. Detritivores consume the remains of plant and animal life, which usually contains enzymes and proteins far too complex to benefit the soil in their original state. By feeding on organic remains, detritivores cycle these complex chemicals through their systems, causing them to undergo chemical reactions that result in the breakdown of their components. As a result, simple and usable nutrients are made available to the soil.

TOPOGRAPHY AND TIME. Then there is the matter of topography, or what one might call landscape—the configuration of Earth's surface, including its relief or elevation. Soil at the top of a hill, for instance, is liable to experience considerable leaching and loss of nutrients. On the other hand, if soil is located in

a basin area, it is likely to benefit from the vitamins and minerals lost to soils at higher elevations, which lose these nutrients through leaching and erosion.

In addition, topography influences the presence or absence of organic material, which is vital if the soil is to sustain plant life. Organic matter in mountainous areas accounts for only 1% to 6% of the soil composition, while in wet lowland regions it may constitute as much as 90% of soil content. Because erosion tends to bring soil, water, and organic material from the highlands to the lowlands, it is no wonder that lowlands are almost always more fertile than the mountains that surround them.

Finally, time is a factor in determining the quality of soil. As with everything else that either is living or contains living things, soil goes through a progression from immaturity to a peak to old age. In the earth sciences, age often is measured not in years, which is an absolute dating method, but by the relative dating technique of judging layers, beds, or strata of earth materials. (For more about studying rock strata as well as relative dating techniques, see Stratigraphy.)



Leaves on the forest floor are an example of humus, a component of the A horizon, or topsoil. *(© Michael Hubrich/Photo Researchers. Reproduced by permission.)*

REAL-LIFE APPLICATIONS

Layers in the Soil

If you dig down into the dirt of your backyard, you will see a miniature record of your regions's geologic history over the past few million years. Actually, most homes in urban areas and suburbs today have yards made of what is called fill dirt—loose earth that has been moved into place by a backhoe or some other earthmoving mechanism. Even though the mixed quality of fill dirt makes it difficult to discern the individual strata, the soil itself tells a tale of the long ages of time that it took to shape it.

Better than a modern fill-dirt yard, of course, would be a sample taken from an older community. Here, too, however, human activities have intervened: people have dug in their yards and holes have been filled back up, for instance, thus altering the layers of soil from what they would have been in a natural state. To find a sample of soil layers that exists in a fully natural state, it might be necessary to dig in a woodland environment.

In any case, anyone with a shovel and a piece of ground that is reasonably untouched—that is, that has not been plowed up recently—can become an amateur soil scientist. Soil scientists study soil horizons, or layers of soil that lie parallel to the surface of Earth and which have built up over time. These layers are distinguished from one another by color, consistency, and composition. A cross-section combining all or most of the horizons that lie between the surface and bedrock is called a soil profile. The most basic division of layers is between the A, B, and C horizons, which differ in depth, physical and chemical characteristics, and age.

TOPSOIL. At the top is the A horizon, or topsoil, in which humus—unincorporated, often partially decomposed plant residue—is mixed with mineral particles. Technically, humus actually constitutes something called the O horizon, the topmost layer. Examples of humus would be leaves piled on a forest floor, pine straw that covers a bare-dirt area in a yard, or grass residue that has fallen between the blades of grass on a lawn. In each case, the passage of time will make the plant materials one with the soil.

Owing to its high organic content, the soil of the A horizon may be black, or at least much darker than the soil below it. Between the A and B horizons is a noticeable layer called the *E horizon,* the depth of which is a function of the particulars in its environment, as discussed earlier. In rough terms, topsoil could be less than a foot (0.3 m) deep, or it could extend to a depth of 5 ft. (1.5 m) or more.

In any case, the E horizon, known also as the eluviation or leaching layer, is composed primarily of sand and silt, built up as water has leached down through the soil. The sediment of the E horizon is nutrient-poor, because its valuable mineral content has drained through it to the B horizon. (The E horizon is just one of several layers aside from the principal A, B, and C layers. We will mention only a few of these here, but soil scientists include several other horizons in their classification system.)

SUBSOIL, REGOLITH, BEDROCK. The appearance and consistency of the soil change dramatically again as we reach the B horizon. No longer is the earth black, even in the most organically rich environments; by this point it is more likely to exhibit shades of brown, since organic material has not reached this far below the surface. Yet subsoil, which is the consistency of clay, is certainly not poor in nutrients; on the contrary, it contains abundant deposits of iron, aluminum oxides, calcium carbonate, and other minerals, leached from the layers above it.

The rock on the C horizon is called regolith, a general term for a layer of weathered material that rests atop bedrock. Neither plant roots nor any other organic material penetrate this deeply, and the deeper one goes, the more rocky the soil. At a certain depth, it makes more sense to say that there is soil among the rocks rather than rocks in the soil.

Beneath the C horizon lies the R horizon, or bedrock. As noted earlier, depths can vary. Bedrock might be only 5–10 ft. deep (1.5–3 m), or it might be half a mile deep (0.8 km) or perhaps even deeper. Whatever the depth, it is here that the solid earth truly becomes solid, and for this reason builders of skyscrapers usually dig down to the bedrock to establish foundations there.

Life Beneath the Surface

The ground beneath our feet—that is, the topmost layer, the A horizon—is full of living things. In fact, there are more creatures below Earth's surface than there are above it. The term creatures in this context includes microorganisms, of which there might be several billion in a sample as small as an acorn. These include decomposers, such as bacteria and fungi, which feed on organic matter, turning fresh leaves and other material into humus. In addition, both bacteria and algae convert nitrogen into forms usable by plants in the surrounding environment (see Nitrogen Cycle).

WORMS. We cannot see bacteria, of course, but almost anyone who has ever dug in the dirt has discovered another type of organism: worms. These slimy creatures might at first seem disgusting, but without them our world could not exist as it does. As they burrow through soils, earthworms mix organic and mineral material, which they make available to plants around them. They also may draw leaves deep into their middens, or burrows, thus furnishing the soil with nutrients from the surface. In addition, earthworms provide the extraordinarily valuable service of aerating the soil, or supplying it with air: by churning up the soil continuously, they expose it to oxygen from the surface and allow air to make its way down below as well.

Nor are these visible, relatively large worms the only ones at work in the soil. Colorless worms called nematodes, which are only slightly larger than microorganisms, also live in the soil, performing the vital function of processing organic material by feeding on dead plants. Some, however, are parasites that live off the roots of such crops as corn or cotton.

ANTS AND LARGER CREATURES. Likewise there are "bad" and "good" ants. The former build giant, teeming mounds and hills that rise up like sores on the surface of the ground, and some species have the capacity to sting, causing welts on human victims. But a great number of ant species perform a positive function for the environment: like earthworms, they aerate soil and help bring oxygen and organic material from the surface while circulating soils from below.

In some areas, much larger creatures call the soil home. Among these creatures are moles, who live off earthworms and other morsels to be

found beneath the surface, including grubs (insect larvae) and the roots of plants. As with ants and earthworms, by burrowing under the ground, they help loosen the soil, making it more porous and thus receptive both to moisture and air. Other large burrowing creatures include mice, ground squirrels, and prairie dogs. They typically live in dry areas, where they perform the valuable function of aerating sandy, gravelly soil.

Soils and Environments

In discussing our imaginary journey through the depths of the soil, it has been necessary to use vague terms concerning depths: "less than a foot," for instance. The reason is that no solid figures can be given for the depth of the soil in any particular area, unless those figures are obtained by a soil scientist who has studied and measured the soil.

Depth is just one of the ways that the soil may vary from one place to another. Earlier we mentioned five factors that affect the character of the soil: parent material, climate, living organisms, topography, and time. These factors determine all sorts of things about the soil—most of all, its ability to support varied life-forms. Collectively, these five factors constitute the environment in which a soil sample exists.

POOR SOILS. A desert environment might be one of immature soil, defined as a sample that has only A and C horizons, with no B horizon between them. On the other hand, the soil in rainforests suffers from just the opposite condition: it has gone beyond maturity and reached old age, when plant growth and water percolation have removed most of its nutrients.

Whether in the desert or in the rainforest, soils near the equator tend to be the "oldest," and this helps explain why few equatorial regions are noted for their agricultural productivity, even though they enjoy otherwise favorable weather for growing crops. Soils there have been leached of nutrients and contain high levels of iron oxides that give them a reddish color. Moreover, red soil is never good for growing crops: the ancient Egyptians referred to the deserts beyond their realm as "the red land," while their own fertile Nile valley was "the black land."

RAINFORESTS. If soil is so poor at the equator, why do equatorial regions such as the Congo or the Amazon River valley in Brazil support the dense, lush rain-forest ecosystems for which they are noted? The answer is that the abundance of organic material at the surface of the soil continually replenishes its nutrient content. The rapid rate of decay common in warm, moist regions further supports the process of renewing minerals in the ground.



The burrowing prairie dog helps aerate sandy, gravelly soil in dry areas. *(© Rich Kirchner/Photo Researchers. Reproduced by permission.)*

This also explains why the clearing of tropical rainforests, an issue that environmentalists called to the world's attention in the 1990s, is a serious problem. When the heavy jungle canopy of tall trees is removed, the heat of the sun and the pounding intensity of monsoon rains fall directly on ground that the canopy would normally protect. With the clearing of trees and other vegetation, the animal life that these plants support also disappears, thus removing organisms whose waste products and bodies would have decayed eventually and enriched the soil. Pounded by heat and water and without vegetation to resupply it, the soil in an exposed rainforest becomes hard and dry.

DESERTS. In deserts the soil typically comes from sandstone or shale parent material, and the lack of abundant rainfall, vegetation, or

KEY TERMS

A HORIZON: Topsoil, the uppermost of the three major soil horizons.

AERATE: To make air available to soil.

ATMOSPHERE: In general, an atmosphere is a blanket of gases surrounding a planet. Unless otherwise identified, however, the term refers to the atmosphere of Earth, which consists of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon (0.07%).

B HORIZON: Subsoil, beneath topsoil and above regolith.

BEDROCK: The solid rock that lies below the C horizon, the deepest layer of soil.

BIOGEOCHEMICAL CYCLES: The changes that particular elements undergo as they pass back and forth through the various earth systems and particularly between living and nonliving matter. The elements involved in biogeochemical cycles are hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur.

BIOSPHERE: A combination of all living things on Earth—plants, mammals, birds, reptiles, amphibians, aquatic life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

C HORIZON: Regolith, which lies between subsoil and bedrock and constitutes the bottommost of the soil horizons.

DECOMPOSERS: Organisms that obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. The principal forms of decomposer are bacteria and fungi.

DECOMPOSITION REACTION: A chemical reaction in which a compound is broken down into simpler compounds or into its constituent elements. In the earth system, this often is achieved through the help of detritivores and decomposers.

DETRITIVORES: Organisms that feed on waste matter, breaking organic material down into inorganic substances that then can become available to the biosphere in the form of nutrients for plants. Their function is similar to that of decomposers, but unlike decomposers—which tend to be bacteria or fungi—detritivores are relatively complex organisms, such as earthworms or maggots.

ECOSYSTEM: A community of interdependent organisms along with the inorganic components of their environment.

EROSION: The movement of soil and rock due to forces produced by water, wind, glaciers, gravity, and other influences. In most cases, a fluid medium, such as air or water, is involved.

FILL DIRT: Loose earth that has been moved into place by a backhoe or some other earthmoving machine, usually as part of a large construction project.

animal life gives the soil little in the way of organic sustenance. For this reason, the A horizon level is very thin and composed of light-colored earth. Then, of course, there are desert areas made up of sand dunes, where conditions are much worse, but even the best that deserts have to offer is not very good for sustaining abundant plant life.

KEY TERMS CONTINUED

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

HUMUS: Unincorporated, often partially decomposed plant residue that lies at the top of soil and eventually will decay fully to become part of it.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

LEACHING: The removal of soil materials that are in solution, or dissolved in water.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals), and oxides, such as carbon dioxide.

PARENT MATERIAL: Mineral fragments removed from rocks by means of weathering. Along with organic deposits, these form the basis for soil.

REGOLITH: A general term describing a layer of weathered material that rests atop bedrock.

SEDIMENT: Material deposited at or near Earth's surface from a number of sources, most notably preexisting rock. There are three types of sediment: rocks, or clastic sediment; mineral deposits, or chemical sediment; and organic sediment, composed primarily of organic material.

SEDIMENTARY ROCK: One of the three major types of rock, along with igneous and metamorphic rock. Sedimentary rock typically has its basis in the deposition, compaction, and cementation of rock that has experienced weathering, though it also may be formed as a result of chemical precipitation. Organic sediment also may be a part of sedimentary rock.

SEDIMENTATION: The process of erosion, transport, and deposition undergone by sediment.

SOIL HORIZONS: Layers of soil, parallel to the surface of Earth, that have built up over time. They are distinguished from one another by color, consistency, and composition.

SOIL PROFILE: A cross-section combining all or most of the soil horizons that lie between Earth's surface and the bedrock below it.

TOPOGRAPHY: The configuration of Earth's surface, including its relief as well as the position of physical features.

WEATHERING: The breakdown of rocks and minerals at or near the surface of Earth due to physical, chemical, or biological processes.

Only those species that can endure a limited water supply—for example, the varieties of cactus that grow in the American Southwest—are able to survive. But lack of water is not the only problem. Desert subsoils often contain heavy deposits of salts, and when rain or irrigation adds water to the topsoil, these salts rise. Thus, watering desert topsoil can make it a worse environment for growth.

RICH SOILS. In striking contrast to the barren soil of the deserts and the potentially barren soil of the rainforest is the rich earth that lies beneath some of the world's most fertile crop-producing regions. On the plains of the midwestern United States, Canada, and Russia, the soil is black—always a good sign for growth. Below this rich topsoil is a thick subsoil that helps hold in moisture and nutrients.

The richest variety of soil on Earth is alluvial soil, a youngish sediment of sand, silt, and clay transported by rivers. Large flowing bodies of water, such as the Nile or Mississippi, pull soil along with them as they flow, and with it they bring nutrients from the regions through which they have passed. These nutrients are deposited by the river in the alluvial soil at its delta, the place where it enters a larger body of water—the Mediterranean Sea and the Gulf of Mexico, respectively. Hence the delta regions of both rivers are extremely fertile.

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SOIL CONSERVATION

CONCEPT

With the rise of the environmentalist movement in the 1960s and afterward, it has become common to speak of conserving natural resources such as trees or fossil fuels. Yet long before humans recognized the need to make responsible use of things taken from the ground, they learned to conserve the ground itself—that is, the soil. This was a hard-won lesson: failure to conserve soil has turned many a fertile farmland into temporary dust bowl or even permanent desert. Techniques such as crop rotation aid in conservation efforts, but communities continue to face hazards associated with the soil. There is, for instance, the matter of leaching, the movement of dissolved substances through the soil, which, on the one hand, can benefit it but, on the other hand, can rob it of valuable nutrients. Issues of soil contamination also raise concerns that affect not just farmers but the population as a whole.

HOW IT WORKS

Billions of Years in the Making

Earth's present wealth of soil is the result of hundreds of millions of years' worth of weathering, erosion, and sedimentation. Once, long ago, there was no soil, only rock, and it took eons' worth of weathering to dislodge particles of those rocks. These rocks, when combined with organic materials, became the basis for soil, but before the soil could even begin to take shape, a number of things had to fall into place. Chief among these was the formation of something that, at first glance, at least, does not seem to have a great deal of bearing on the soil: the atmosphere.

In combination with water in the hydrosphere (e.g., streams and rivers) as well as water in the form of evaporated moisture and precipitation in the air itself, the blanket of gases we call our atmosphere has been essential to the formation and sustenance of Earth's soil. This importance goes beyond the obvious point that rain transports water to the soil, thus making possible the abundance of plant life that grows in it. Rain, of course, is of unquestionable importance, but it is only one of several factors associated with the atmosphere (including the water vapor it contains) that have a role in shaping soil as we know it.

To move weathered rocks from highlands to lowlands, where they can become sediment and eventually begin to form soil, it is necessary to subject the rocks themselves to a process of erosion. And erosion—aside from erosion caused by gravity, which usually is considered weathering—can take place only when an atmosphere exists, along with water in the air and on the land. The chief agents of erosion are wind, water (both flowing and in the form of precipitation), and frozen water in the form of icy glaciers, all of which depend on an atmosphere or water or both (see Glaciology).

Erosion transports not only rock sediment but organic material as well. Together, these two ingredients are as essential to making soil as tea bags and water are to making tea. Obviously, the greater the organic content, the richer the soil, and here again the air plays a part. It is important that deeper layers of soil receive a supply of air from the surface to sustain the life of subter-

ranean organisms, who not only process nutrients through the soil but (by their burrowing activities) also aerate it, or make air available to it.

A Product of Its Environment

Soil, like most people, is a product of the environment in which it was formed. That environment has five major influencing factors: the nature of the "parent material," or the rock from which the soil was derived; the local climate; the presence of living organisms; local topography; and the passage of time.

Specific classes of mineral break apart in characteristic ways, and the size of the pieces into which the original weathered rock is broken has a great deal to do with the character of the soil that it forms. This does not mean, however, that relatively large rock pieces necessarily will yield the worst soils, since erosive forces will continue to work on the rock, pulling out its nutrient-rich mineral wealth and gradually acting to break it apart.

As for climate, it is clear that rain and sun are essential for the growth of plant matter, but, of course, too much of either or both is harmful. (See Soil for a discussion of soils in rainforests.) Plants aid the soil by dying and feeding it with more organic material, but they are not the only types of organism in the soil. Indeed, the soil constitutes an ecosystem in and of itself, a realm rich in biodiversity, in which various biogeochemical cycles are played out, and through which energy flows as part of the operation of the larger Earth system.

The underground world teems with creatures ranging from bacteria to moles and prairie dogs (in some regions), each of which fulfills a function. These functions include aerating the soil by burrowing; processing material though ingestion and elimination of waste, thus converting compounds into nutrients that the soil can use; and mixing organic material with minerals. Organisms' final contribution to the soil comes when they die, as their bodies become material that feeds the earth through decomposition.

Topography, or elevation, plays a major role in making possible erosion, itself a process that can be either beneficial or detrimental. The question of whether it is one or the other may be a matter of perspective, or rather elevation. From the standpoint of lowland areas, which receive the wealth of the upland areas in the form of nutrient-rich runoff carried by gravity or flowing media, such as wind or water, erosion is a good thing. Matters do not look as good from the viewpoint of the mountains, which lose much of their best soil to low-lying areas.

The influence of time in shaping soils—as well as much else about the soil itself—can be appreciated by studying soil horizons, the various strata, or layers, of soil that lie beneath the surface. The most basic division of layers is between the A, B, and C horizons, which differ in depth and physical and chemical characteristics as well as age.

soil horizons. Above the A horizon, or topsoil, lies humus, decomposing organic material that eventually will become soil. The A horizon itself contains a large amount of organic matter, and thus it may be black, or at least much darker than the soil below it. Between the A and B horizons is a sandy, silty later called the E horizon. Then comes the B horizon, or subsoil, which starts at a depth as shallow as 1 ft. (0.3 m) or deeper than 5 ft. (1.5 m).

Lacking a great deal of organic material but still rich in nutrients, the B horizon has a sizable impact on the A horizon. Minerals—both healthful and harmful—may rise up from the B to the A horizon, and the ability of the B horizon to hold in moisture from above greatly affects the moisture of the A horizon soil. (See Soil for a discussion of how salt deposits in the B horizon affect topsoil in deserts.) Together, A and B horizons constitute what is called the *solum,* or true soil.

The C horizon is called *regolith.* It is the home for the rocks of the parent material, which has given up much of its nutrient riches in fortifying the soil that lies above it. This far below the surface, there is no sign of plant or animal life, and below the C horizon is the R horizon, or bedrock—the top of the layers of rock and metal that descend all the way to the planet's core. Once again depths vary, with bedrock as shallow as 5–10 ft. (1.5–3 m) or as deep as 0.5 mi. (0.8 km) or more.

Differences Between Soils

The depth of the soil is a measure of wealth—wealth, that is, in terms of natural resources. A sheath over much of the solid earth, soil separates the planet's surface from its rocky interior and preserves the lives of the plants and animals



A cloud of topsoil is picked up by the wind near Boise City, Oklahoma, during the dust bowl of the 1930s. In some cases, wind removed 3-4 in. (7.6-10.6 cm) of topsoil, turning acreage that once rippled with wheat into a desertlike wasteland. *(AP/Wide World Photos. Reproduced by permission.)*

that live on and in it. It receives rain and other forms of precipitation, which it filters through its layers, as we discuss later, in the context of leaching. Thus, it not only provides water to organisms above and below its surface but also helps prevent flooding by acting as a reservoir.

A great deal of soil's volume is air, for which it also acts as a reservoir. Underground creatures depend on this air and also help circulate it by burrowing. This circulation, in turn, provides oxygen to the roots of plants and makes the soil more hospitable to growth. Even though soil performs these and other life-preserving functions, it would be a mistake to assume that all soils are the same. In fact, the U.S. Department of Agriculture has identified 11 major soil orders, each of which is divided into suborders, groups, subgroups, families, and series.

The specificity of soil types, as reflected in the identification and naming of soil series, illustrates the complexity of what at first seems a very simple thing. In fact, soils can be extremely specific, with names that reflect local landmarks. If soils share enough similarities, they are grouped together in a soil series, but it is safe to say that there are thousands of individual soil types on Earth.

Conserving Soil

On a broad level, there are certain types of environment more or less favorable to the formation of rich soil. Some of these types are discussed in the essay Soil, and specific examples of environmental problems are provided later in this essay. Yet almost any environment can become unfavorable to plant growth if proper soil-conservation procedures are not observed.

The phrase soil conservation refers to the application of principles for maintaining the productivity and health of agricultural land by control of wind- and water-induced soil erosion. For the remainder of this essay, we examine the dangers involved in such erosion and the use of measures to prevent it. In so doing, we give the matter of soil conservation a somewhat larger scope than the preceding definition might suggest. Since soil affects the world far beyond farms, it seems only fitting to approach it not as a concern merely of agriculture but of the environment in general.

Erosion is spoken of here in a general sense, but for a more in-depth discussion of erosive processes, see Erosion. Mass Wasting examines dramatic erosion-related phenomena, such as landslides. Biogeochemical Cycles contains some

discussion of erosion, inasmuch as it helps circulate life-sustaining chemical elements throughout the various earth systems. Indeed, it is important to remember that erosion is not always negative in its results; on the contrary, it is a valuable process by which landforms are shaped. The erosive processes we explore here, however, generally contribute to the loss of soil health and productivity.

REAL-LIFE APPLICATIONS

The Dust Bowl

When people mismanage agricultural lands or when natural forces otherwise conspire to destroy soil, the results can be devastating. One of the most dramatic examples occurred in what came to be known as the dust bowl. This was the name given to a wide area covering Texas, Oklahoma, Kansas, and even agricultural parts of Colorado during the years 1934 and 1935. Over the course of a few months, once-productive farmlands turned into worthless fields of stubble and dust, good for almost nothing and highly vulnerable to violent wind erosion.

And wind erosion came, scattering vast quantities of soil from the Great Plains of the Midwest to the Atlantic Seaboard. The classic 1939 film *The Wizard of Oz* sets its fantastic, otherworldly story against this backdrop, and to viewers in the late 1930s the tornado that swept Dorothy from her Kansas farmland into the world of Oz was all too real. The only difference was that no magical adventure awaited victims of the real-life tornadoes and other windstorms.

The fate of the dust bowl farmers, many of whom lost everything, was dramatized in the novel *The Grapes of Wrath* by John Steinbeck in 1939 as well as in the acclaimed motion picture that followed a year later. A perhaps equally eloquent tribute appeared in the form of the American photographer Dorothea Lange's photographs of dust bowl refugees. The images etched by Lange are unforgettable: in one a woman stares into the distance, her face a landscape of despair, as her children huddle next to her, their eyes hidden from the camera. In another a man, obviously exhausted from months or years of overwork, hardship, and fear, sits behind the wheel of a truck, gazing somewhere beyond the camera lens. Like the woman, he seems to be looking into a future that offers scant hope.

CAUSES OF THE DUST BOWL. What happened? The sad fact is that in the years leading up to the early 1930s, the future dust bowl farmlands had seemed remarkably productive, and farmers continued to be pleasantly surprised, year after year, at the abundant yields they could draw from each field. In fact, farmers were unwittingly preparing the way for vast erosion by overcultivating the land and not taking proper steps to preserve its moisture against drought. This was particularly unfortunate because farmers in the 1930s had long known about the principle of crop rotation as a means of giving the soil a rest in order to restore its nutrients. Yet the farmers of the plains tried to push their crops to yield more and more, and for a time it worked, though at great future expense to the land.

One is tempted to see in the agricultural world of the U.S. Midwest parallels to the foolhardy attitude that, just a few years earlier, created a boom on Wall Street, followed by the devastating stock market crash of October 29, 1929, that ushered in the Great Depression. Certainly the ravages of the dust bowl, when they came, were particularly unwelcome in a land already reeling from several years of widespread unemployment and a sagging economy. And though there was no cause-effect relationship between the Wall Street crash and the dust bowl, there is no question that both were brought about in large part by a lack of planning for the future and by a naive belief that it is possible to get "something for nothing"—that is, to get more out of the world (whether the world of finances or the natural world) than one puts into it.

In some places farmers alternated between wheat cultivation and livestock grazing on particular plots of land. Thus, the hooves of the cattle damaged the soil, which had been weakened by raising wheat. The land was therefore ready to become the site of a full-fledged natural disaster, and, at the height of the depression, natural disaster came in the form of high winds. The winds in some cases removed topsoil as much as 3–4 in. (7–10 cm) thick. Dunes of dust as tall as 15–20 ft. (4.6–6.1 m) formed, turning acreage that once had rippled with wheat into desertlike wastelands.

Erosion Control in Action

Today the farmlands of the plains states long since have recovered, and American farmers have benefited from the lessons learned in the dust bowl. Out of the dust bowl years came the establishment, in 1935, of the Soil Conservation Service, a federal agency charged with implementing erosion-control practices. (The Soil Conservation Service was the predecessor of the modern-day Natural Resources Conservation Service.) In the wake of the legislation creating the agency, signed into law by President Franklin D. Roosevelt (1882–1945), states passed laws creating nearly 3,000 local soil conservation districts.

If one passes through agricultural lands today, one is likely to see signs identifying the local conservation district. Even more important, the lands themselves are a testament to principles put into practice as an outgrowth of the dust bowl years. For instance, instead of alternating one year of wheat with one year in which a field lies fallow, or unused, farmers in the dust bowl region discovered that a three-year cycle of wheat, sorghum, and fallow land worked much better. They also planted trees to serve as barriers against wind.

Erosion control legislation. Concerns over soil conservation in America did not end with the dust bowl. As United States farm production soared in the 1970s, American farms enjoyed such a great surplus that U.S. farmers increasingly began to sell their crops overseas—most notably, to the Soviet Union. While some Americans were upset to see the farmers of the Midwest selling wheat to the Communists in Moscow, others saw in this act a testament to the failure of the Soviet agricultural system and to the strength of U.S. farming. In the wake of these increased exports, farmers were encouraged to cultivate even marginal croplands to increase profits, thus heightening the vulnerability of their lands to erosion.

What followed was not another dust bowl, however; instead, the experience of the 1970s and 1980s shows just how much American farmers, legislators, and others had learned from the 1930s. Environmental activists in the 1970s, concerned over water quality, helped return public interest to the problem of soil erosion. They called attention to the flow of nutrients from croplands into water resources, most notably leaching of nitrogen and phosphorus that choked lakes with eutrophication (see Biogeochemical Cycles). As a result of public concerns over these and related issues, Congress in 1977 passed the Soil and Water Resources Conservation Act, mandating the conservation of soil, water, and other resources on private farmlands and other properties.

In 1985 the Food Security Act further served to encourage steps toward the reduction of soil erosion. Some 45 million acres (18 million hectares) of land vulnerable to erosion were removed from intensive cultivation by the act. The legislation also forbade the conversion of rangelands into agricultural fields, which would have raised great potential for erosion and depletion of already vulnerable soil. In addition, the act required farmers to develop and maintain practices for the control of erosion on lands susceptible to that threat.

Barrier and cover. Soil-conservation practices fall under two headings: barrier and cover. Under the barrier approach, various structures act as a wall against water runoff, wind, and the movement of soil. Among such structures are banks, hedgerows, walls of earth or other materials, and silt fences such as one sees at construction sites. The cover approach is devoted to the idea of maintaining a heavy soil cover of living and dead plant material. This is achieved through the use of mulch, cover crops, and other techniques.

Local governments and property owners in nonagricultural lands often apply both the cover and barrier approaches, planting trees as well as grass not simply to beautify the land but also to hold the soil in place. Land has to have some sort of vegetative protection to stand between it and the forces of wind and water erosion, and the two approaches together serve to protect soil against nature's onslaught.

Leaching

Like erosion, leaching—the movement of dissolved substances with water percolating through soil—can be both positive and negative. For any plot of land, assuming the rate of water input is greater than the rate of water loss through evaporation, water has to go somewhere, so it leaves the site by moving downward. Eventually it either reaches the deep groundwater or passes through subterranean springs to flow into the surface waters of streams, rivers, and lakes.

Along the way, the leached water carries all sorts of dissolved substances, ranging from nutrients to contaminants. The threat of the latter has led to widespread concern in the United States over the leaching of toxins into water supplies, and in 1980 this concern spurred a massive piece of legislation called CERLA (Comprehensive Environmental Response, Compensation, and Liability Act), better known as Superfund. Six years later, in 1986, Congress updated CERLA with the Superfund Amendments and Reauthorization Act. These laws provided for a vast array of measures directed toward environmental cleanup, including the removal of chemicals and other toxins in soil.

Drastic measures such as those outlined in CERLA and other legislation may be required for the cleanup of artificial materials introduced into soils and groundwater. But for human waste and other more natural forms of toxin, nature itself is able to achieve a certain amount of cleanup on its own. In a septic-tank system, used by people who are not connected to a municipal sewage system, bacteria process wastes, removing a great deal of their toxic content in the tank itself. The wastewater leaves the tank and passes through a filtration system, in which the water leaches through layers of gravel and other filters that help remove more of its harmful content. As the wastewater percolates from the filtration system through the soil (usually well below the A horizon by this point), it is purified further before it enters the groundwater supply.

Not only does leaching help purify the water that passes through the soil, it also is an important part of the soil-formation process, inasmuch as it passes nutrients to the depths of the A horizon and into the B horizon. Its ability to pass along nutrients is not always beneficial, and in some ecosystems, large amounts of dissolved nitrogen are lost to soil as a result of leaching. In such a situation, soil typically is fertilized with nitrate, a form of the element with which soil often has difficulty binding (see Nitrogen Cycle). For this reason, nitrate tends to leach easily, leading to an overabundance of nitrogen in the lower levels of the soil and in the groundwater. This condition, known as nitrogen saturation, can influence the eutrophication of waters (see Biogeochemical Cycles for an explanation of eutrophication) and can cause the decline and death of trees on the surface.

Desertification

Much of North Africa lies under the cover of a vast desert, the Sahara. By far the world's largest desert, the Sahara today spreads across some 3.5 million sq. mi. (9.06 million sq km), an area larger than the continental United States. Only about 780 acres (316 hectares) of it, or little more than 1 sq. mi. (2.6 sq km), is fertile. The rest is mostly stone and dry earth with scattered shrubs—and, here and there, the rolling sand dunes typically used to depict the Sahara in movies.

Given the forbidding moonscape of the Sahara today, it might be surprising to learn that just 8,000 years ago—the blink of an eye in terms of geologic time—it was a region of flowing rivers and lush valleys. For thousands of years it served as a home to many cultures, some of them quite advanced, to judge from their artwork. Though they left behind an extraordinary record in the form of their rock-art paintings and carvings, which show an understanding of realistic representation that would not be matched until the time of the Greeks, the identity of the early Saharan peoples themselves remains largely a mystery.

Instead of identifying them by the name of a nationality or empire, archaeologists divide the phases of the early Saharan culture according to a set of four names that collectively tell the story of the region's progressive transformation into a desert. First was the Hunter period, from about 6000 to about 4000 B.C., when a Paleolithic, or Old Stone Age, people survived by hunting the many wild animals then available in the region. Next came the Herder period, from about 4000 to 1500 B.C. As their name suggests, these people maintained herds of animals and also practiced basic agriculture.

As the Sahara became drier and drier, however, there were no more herds. Egyptians began bringing in domesticated horses to cross the desert: hence the name of the Horse period (*ca.* 1500–*ca.* 600 B.C.) By about 600 B.C., not even horses could survive in the forbidding climate. There was only one creature that could survive: the hardy, seemingly inexhaustible camel. Thus began the Camel era, which continues to the present day.

Attempts to control desertification. As with the dust bowl, the first question one wants to ask when confronted



A camel caravan in the Sahara. The world's largest desert, it covers 3.5 million sq. mi. (9 million sq km), but 8,000 years ago this was a region of lush valleys and flowing rivers. *(© Tom Hollyman/Photo Researchers. Reproduced by permission.)*

with a story such as that of the Sahara, is "What happened?" The answer is much more complex, just as the effects of desertification—the slow transformation of ordinary lands to desert—are much more permanent than those of the erosion associated with the dust bowl. Desertification does not always result in what people normally think of as a desert. It is rather a process that contributes toward making a region more dry and arid, and because it is usually gradual, it can be reversed in some cases. But doing so represents a vast challenge.

In 1977 the United Nations (UN), in the form of the UN Conference on Desertification in Nairobi, Kenya, set out to address the spread of the Sahara into the Sahel, an arid region that stretches south of the desert. Some 700 delegates from almost 100 countries adopted a number of measures designed to halt the spread of desertification in that region and others by the year 2000.

Even though there have been some successes, the Sahel region today remains a blighted area where famine is common, and this state of affairs is not entirely the result of the natural causes addressed in the conference's resolutions. Poor government management and a near-constant state of civil war in such countries as Ethiopia have played at least as important a role in spreading famine as nature itself. During the 1980s, in fact, the government of Ethiopia (at that time a Marxist-Leninist state) deliberately withheld food supplies, shipped to it from the West, as a way of exerting pressure on rebel factions and other groups it wished to subdue.

THE EXAMPLE OF IRAQ. The arid regions of Iraq provide another example of how human influences can result in desertification. Once that country, known in ancient times as Mesopotamia, was among the greenest and most lush places in the known world. For this reason, historians today use the name Fertile Crescent to describe an arc from the deltas of the Tigris and Euphrates rivers in Mesopotamia to the mouth of the Nile in Egypt. Today, of course, Iraq is mostly a dust-colored land of bare trees and brush.

What happened? Agricultural mismanagement certainly played a role, as did the simple exhaustion of the soil by some 6,000 years of human civilization. Indeed, since the Fertile Crescent was perhaps the first area settled by agricultural societies long before the beginning of full-fledged civilization as such in about 3500

KEY TERMS

A HORIZON: Topsoil, the uppermost of the three major soil horizons.

AERATE: To make air available to soil.

B HORIZON: Subsoil, beneath topsoil and above regolith.

BEDROCK: The solid rock that lies below the C horizon, the deepest layer of soil.

BIOGEOCHEMICAL CYCLES: The changes that particular elements undergo as they pass back and forth through the various earth systems and particularly between living and nonliving matter. The elements involved in biogeochemical cycles are hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur.

C HORIZON: Regolith, which lies between subsoil and bedrock and constitutes the bottommost of the soil horizons.

DECOMPOSERS: Organisms that obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. The principal forms of decomposer are bacteria and fungi.

DECOMPOSITION REACTION: A chemical reaction in which a compound is broken down into simpler compounds or into its constituent elements. In the earth system, this often is achieved through the help of detritivores and decomposers.

DETRITIVORES: Organisms that feed on waste matter, breaking organic material down into inorganic substances that then can become available to the biosphere in the form of nutrients for plants. Their function is similar to that of decomposers; however, unlike decomposers—which tend to be bacteria or fungi—detritivores are relatively complex organisms, such as earthworms or maggots.

ECOSYSTEM: A community of interdependent organisms along with the inorganic components of their environment.

EROSION: The movement of soil and rock due to forces produced by water, wind, glaciers, gravity, and other influences. In most cases, a fluid medium, such as air or water, is involved.

EUTROPHICATION: A state of heightened biological productivity in a body of water, which is typically detrimental to the ecosystem in which it takes place. Eutrophication can be caused by an excess of nitrogen or phosphorus in the form of nitrates and phosphates, respectively.

HUMUS: Unincorporated, often partially decomposed plant residue that lies at the top of soil and eventually will decay fully to become part of it.

B.C., it is safe to say that the region has been under cultivation for several thousand years longer—perhaps 8,000 or even 10,000 years. Direct human action and malice also may have played a role: some historians believe that the Mongols, during their brutal invasion in the 1250s, so badly devastated the farmlands and irrigation channels of Iraq that the land never recovered.

SOME CAUSES OF DESERTIFICATION. With regard to human involvement in the desertification process, it is not necessary for a society to be advanced agriculturally to do long-term damage to the soil. The Pueblan

KEY TERMS CONTINUED

LANDFORM: A notable topographical feature, such as a mountain, plateau, or valley.

LEACHING: The removal of soil materials that are in solution, or dissolved in water.

MASS WASTING: The transfer of earth material down slopes by processes that include creep, slump, slide, flow, and fall. Also known as *mass movement.*

MINERAL: A naturally occurring, typically inorganic substance with a specific chemical composition and a crystalline structure.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals) and oxides, such as carbon dioxide.

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SEDIMENTATION: The process of erosion, transport, and deposition undergone by sediment.

SOIL CONSERVATION: The application of principles for maintaining the productivity and health of agricultural land by control of wind- and water-induced soil erosion. The term also may be applied more broadly to encompass the maintenance and protection of nonagricultural soils.

SOIL HORIZONS: Layers of soil, parallel to the surface of the earth, which have built up over time. These layers are distinguished from one another by color, consistency, and composition.

SOIL PROFILE: A cross-section combining all or most of the soil horizons that lie between Earth's surface and the bedrock below it.

WEATHERING: The breakdown of rocks and minerals at or near the surface of Earth due to physical, chemical, or biological processes.

culture of what is now the southwestern United States depleted an already dry and vulnerable region after about A.D. 800 by removing its meager stands of mesquite trees. And though human causes, in the form of either mismanagement or deliberate damage, have contributed toward desertification, sometimes nature itself is the driving force.

Long-term changes in rainfall or general climate as well as water erosion and wind erosion such as caused the dust bowl can turn a region into a permanent desert. An ecosystem may survive short-term drought, but if soil is forced to go too long without proper moisture, it sets in motion a chain reaction in which plant life dwindles and, with it, animal life as well. Thus, the soil

is denied the fresh organic material necessary to its continued sustenance, and a slow, steady process of decline begins.

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GEOCHEMISTRY

BIOGEOCHEMICAL CYCLES

THE CARBON CYCLE

THE NITROGEN CYCLE

BIOGEOCHEMICAL CYCLES

CONCEPT

Of the 92 elements produced in nature, only six are critical to the life of organisms: hydrogen, carbon, nitrogen, oxygen, phosphorus, and sulfur. Though these elements account for 95% of the mass of all living things, their importance extends far beyond the biosphere. Hydrogen and oxygen, chemically bonded in the form of water, are the focal point of the hydrosphere, while oxygen and nitrogen form the bulk of the atmosphere. All six are part of complex biogeochemical cycles in which they pass through the biosphere, atmosphere, hydrosphere, and geosphere. These cycles circulate nutrients through the soil into plants, microbes, and animals, which return the elements to the earth system through chemical processes that range from respiration to decomposition.

HOW IT WORKS

The Elements

An element is a substance composed of a single type of atom, meaning that it cannot be broken down chemically to make a simpler substance. They are listed on the periodic table of elements, a chart that renders them in order of their atomic numbers, or the number of protons in the nucleus of the atom. The elements we want to discuss in the context of biogeochemical cycles are all low in atomic number, starting with hydrogen, which has just one proton in its nucleus. In the following list, the elements are cited by atomic number along with their chemical symbols, or the abbreviation by which they are known to chemists.

Elements Involved in Biogeochemical Cycles

- 1. Hydrogen (B)
- 6. Carbon (C)
- 7. Nitrogen (N)
- 8. Oxygen (O)
- 15. Phosphorus (P)
- 16. Sulfur (S)

Given the fact, as noted earlier, that 92 elements appear in nature, it should come as no surprise that the highest atomic number for any naturally occurring element is 92, for uranium. Beyond uranium there are about two dozen artificially created elements, but they are of little interest outside the realm of certain specialties in chemistry and physics. The naturally occurring elements are the ones that matter to the earth sciences, and of these elements, only a handful play a significant role.

In the essays Minerals and Economic Geology, other elements—most notably silicon—are discussed with regard to their importance in forming minerals, rocks, and ores. Though they are critical to Earth's systems, elements other than the six discussed here play no role in biogeochemical cycles. Indeed, it is a fact of the physical sciences that not all elements are created equal: certainly, the universe is not divided evenly 92 ways, with equal amounts of all elements. In fact, hydrogen and helium account for 99% of the mass of the entire universe.

ABUNDANCE. On Earth the ratios are quite different, however. Oxygen and silicon constitute the preponderance of the known mass of Earth's crust, while nitrogen and oxygen form the overwhelming majority of the atmosphere. Hydrogen is proportionally much, much less abundant on Earth than in the universe as a

whole, but owing to its role in forming water, a substance essential to the sustenance of life, it is unquestionably of great significance.

The two following lists provide rankings for the abundance of the six elements discussed in this essay. The first table shows their ranking and share in the entire known mass of the planet, including the crust, living matter, the oceans, and atmosphere. The second shows their relative abundance and ranking in the human body.

Abundance of Selected Elements on Earth (Ranking and Percentage)

- 1. Oxygen (49.2%)
- 9. Hydrogen (0.87%)
- 12. Phosphorus (0.11%)
- 14. Carbon (0.08%)
- 15. Sulfur (0.06%)
- 16. Nitrogen (0.03%)

Abundance of Selected Elements in the Human Body (Ranking and Percentage)

- 1. Oxygen (65%)
- 2. Carbon (18%)
- 3. Hydrogen (10%)
- 4. Nitrogen (3%)
- 6. Phosphorus (1%)
- 9. Sulfur (0.26%)

Several things are interesting about these figures. First and most obviously, there is the fact that the ranking of all these elements (with the exception of oxygen) is relatively low in the total known elemental mass of Earth, whereas their ranking is much, much higher within the human body. This is significant, given the fact that these elements are all essential to the lives of organisms.

Furthermore, note that it does not take a great percentage to constitute an "abundant" element: even nitrogen, with its 0.03% share of Earth's total known mass, still is considered abundant. The presence of the vast majority of elements on Earth is measured in parts per million (ppm) or even parts per billion (ppb).

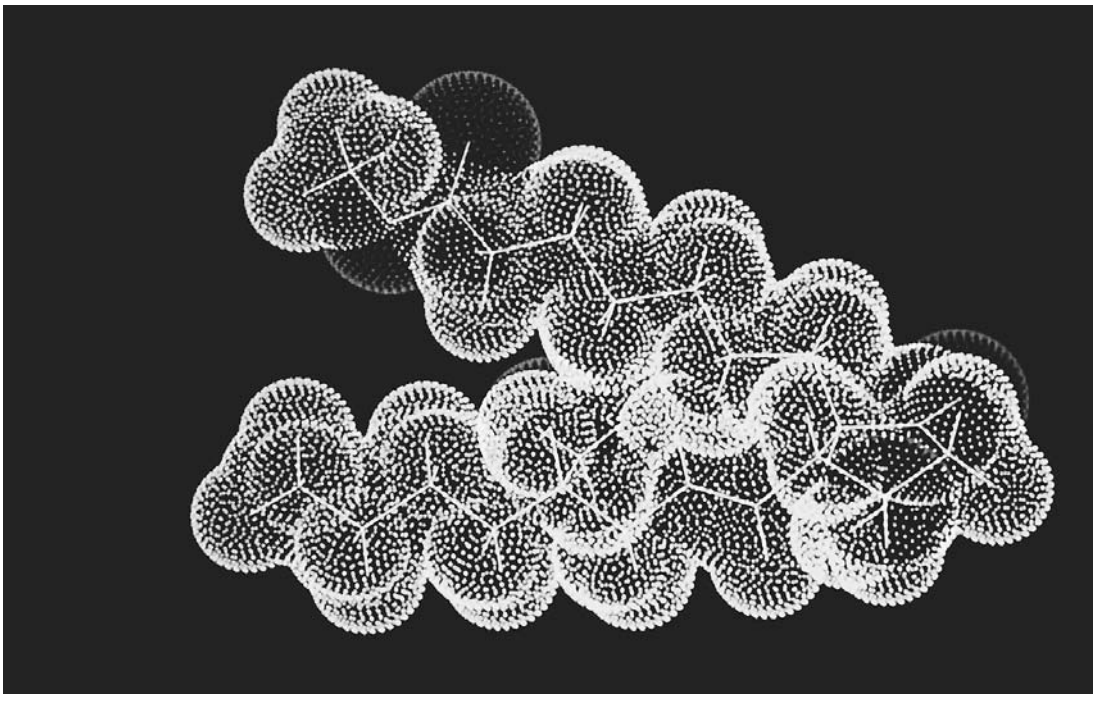
Chemistry and Geochemistry

In a general sense, chemistry can be defined as an area of the physical sciences concerned with the composition, structure, properties, and changes of substances, including elements, compounds, and mixtures. This definition unites the phases in the history of the development of the discipline, from early modern times—when it arose from alchemy, a set of mystical beliefs based on the idea that ordinary matter can be perfected—to modern times. Our modern understanding of chemistry, however, is quite different from the model of chemistry that prevailed until about 1800, a difference that relates to a key discovery: the atom.

This change, in fact, should be described not in terms of a discovery so much as the development of a model. Long before chemists and physicists comprehended the structure of the atom, they developed an understanding of all chemical substances as composed of atomic units, each representing one and only one element. Until the development of this model—thanks to a number of chemists, most notably, John Dalton (1766–1844) of England, Antoine Lavoisier (1743–1794) of France, and Amedeo Avogadro (1776–1856) of Italy—chemistry was concerned primarily with mixing potions and observing their effects. Thanks to the atomic model, chemists never again would confuse mixtures with chemical compounds.

Chemical reactions. The difference between a mixture and a compound goes to the heart of the distinction between physics and chemistry. A mixture, such as coffee, is the result of a physical process—in this case, the heating of water and coffee beans—and the result does not have a uniform chemical structure. On the other hand, a compound results from chemical reactions between atoms, which form enormously powerful bonds in the process of joining to create a molecule. A molecule is the basic particle of a compound, just as an atom is to an element. It should be noted that some elements, such as nitrogen, typically appear in diatomic form, that is, two atoms bond to form a molecule of nitrogen.

A substance may undergo physical changes without experiencing any alteration in its underlying structure; on the other hand, a chemical reaction makes a fundamental change to the substance. In a chemical reaction, a substance may experience a change of state (i.e., from solid to liquid or gas) without undergoing any physical process of being heated or cooled by an outside source. Chemical reactions involve the breaking of bonds between atoms in a molecule and the formation of new bonds. As a result, an entirely new



Molecular structure. A compound is formed by chemical reactions between atoms, which join together to make molecules. *(© Blair Seitz/Photo Researchers. Reproduced by permission.)*

substance is created—something that could never be achieved through mere physical processes.

REAL-LIFE APPLICATIONS

Geochemistry

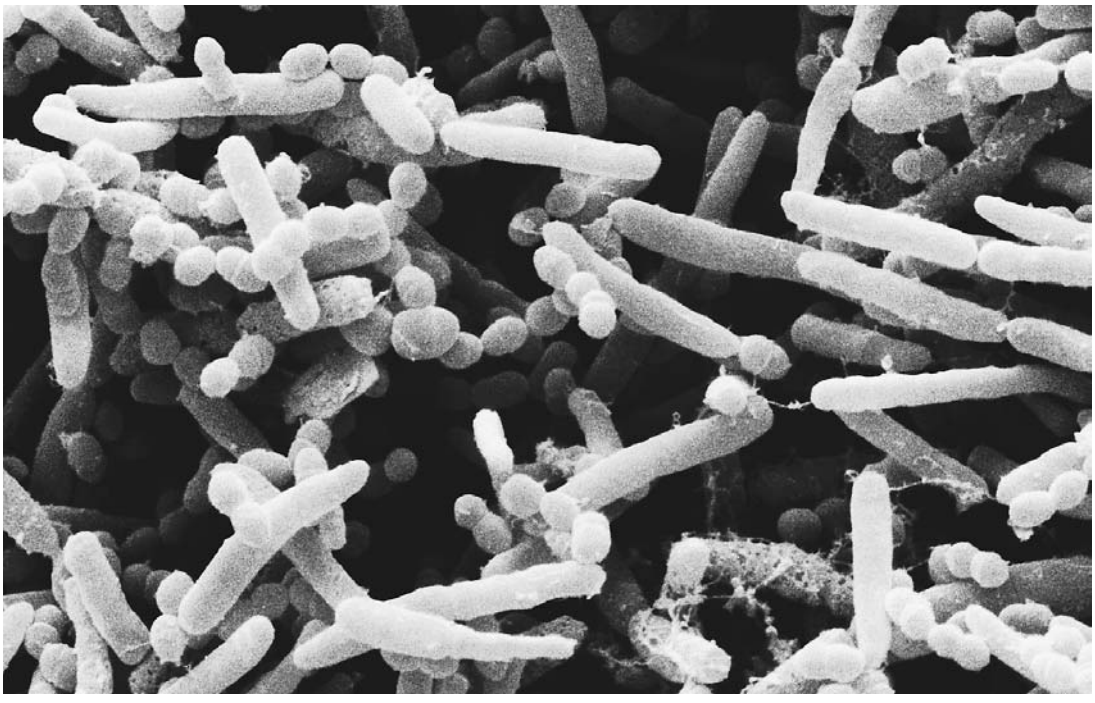
Just as geochemistry is a branch of the geologic sciences that weds physics and geology, so there is a geologic subdiscipline, geochemistry, in which chemistry and the geologic sciences come together. Geochemistry is concerned with the chemical properties and processes of Earth—in particular, the abundance and interaction of chemical elements and their isotopes. (Isotopes are atoms that have an equal number of protons, and hence are of the same element, but differ in their number of neutrons. Isotopes may be either stable or unstable, in which case they are subject to the emission of high-energy particles. Some elements have numerous stable isotopes, others have only one or two, and some have none.)

Before the mid–twentieth century, geochemistry had a relatively limited scope, confined primarily to the identification of elements in rocks and minerals and the determination of the relative abundance of those elements. Since that time, however, this subdiscipline has come to encompass many other concerns, particularly those discussed in the present context. Geochemistry today focuses on such issues as the recycling of elements between the various sectors of the earth system, especially between living and nonliving things.

Biogeochemical Cycles and Earth Systems

The changes that a particular element undergoes as it passes back and forth through the various earth systems, and particularly between living and nonliving matter, are known as biogeochemical cycles. The four earth systems involved in these cycles are the atmosphere, the biosphere (the sum of all living things as well as formerly living things that have not yet decomposed), the hydrosphere (the entirety of Earth's water except for vapor in the atmosphere), and the geosphere. The last of these spheres is defined as the upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

Carbon, for instance, is present in all living things on Earth. Hence, the phrase *carbon-based life-form,* a cliché found in many an old science-



Bacteria begin the process of decomposition of organic waste, breaking down plant matter and converting it into compost. *(© Scimat/Photo Researchers. Reproduced by permission.)*

fiction movie, is actually a redundancy: *all* lifeforms contain carbon. In the context of the physical sciences, *organic* refers to all substances that contain carbon, with the exception of oxides, such as carbon dioxide and carbon monoxide, and carbonates, which are found in minerals. Still, carbon circulates between the organic world and the inorganic world, as when an animal exhales carbon dioxide.

The carbon cycle is of such importance to the functioning of Earth that it is discussed separately (see Carbon Cycle). So, too, is the nitrogen cycle (see Nitrogen Cycle), whereby nitrogen passes between the soil, air, and biosphere as well as the hydrosphere. The hydrosphere, as noted earlier, is based on a single substance, water, created by the chemical bonding of hydrogen and oxygen, and it is likewise discussed in detail elsewhere (see Hydrologic Cycle).

Despite the emphasis here on carbon in the biosphere, nitrogen in the geosphere, and hydrogen and oxygen in the hydrosphere, it should be noted that biogeochemical cycles involving these four elements take them through all four "spheres." The same is true of sulfur, whose biogeochemical cycle is discussed later in this essay. On the other hand, phosphorus, also discussed later, is present in only three of Earth's systems; it plays little role in the atmosphere.

Decomposers and Detritivores

Most biogeochemical cycles involve a special type of chemical reaction known as decomposition, and for this to take place, agents of decomposition—known as decomposers and detritivores—are essential. Decomposition occurs when a compound is broken down into simpler compounds or into its constituent elements. This is achieved primarily by decomposers, organisms that obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products.

The principal forms of decomposer are bacteria and fungi. These creatures carry enzymes, which they secrete into the materials they consume, breaking them down chemically before taking in the products of this chemical breakdown. They thus take organic matter and render it in inorganic form, such that later it can be taken in again by plants and returned to the biosphere.

Detritivores are much more complex organisms, but their role is similar to that of decom-

posers. They, too, feed on waste matter, breaking this organic material down into inorganic substances that then can become available to the biosphere in the form of nutrients for plants. Examples of detritivores are earthworms and maggots. As discussed in Energy and Earth, detritivores are key players in the food web, the set of nutritional interactions—sometimes called a food chain—between living organisms.

Phosphorus and the Phosphorus Cycle

There are a few elements that were known in ancient or even prehistoric times, examples being gold, iron, lead, and tin. The vast majority, on the other hand, have been discovered since the beginning of the modern era, and the first of them was phosphorus, which is also the first element whose discoverer is known.

In 1674 the German alchemist Hennig Brand (*ca.* 1630–*ca.* 1692) was searching for the philosopher's stone, a mythical substance that allegedly would turn common or base metals into gold. Convinced that he would find this substance in the human body, Brand evaporated water from a urine sample and burned the precipitate (the solid that remained) along with sand. The result was a waxy, whitish substance that glowed in the dark and reacted violently with oxygen. Brand named it phosphorus, a name derived from a Greek term meaning "light-bearer."

Owing to its high reactivity with oxygen, phosphorus is used in the production of safety matches, smoke bombs, and other incendiary devices. It is also important in various industrial applications and in fertilizers. In fact, ancient humans used phosphorus without knowing it when they fertilized their crops with animal bones.

Phosphates. In the early 1800s, chemists recognized that the critical component in bones was phosphorus, which plants use in photosynthesis—the biological conversion of energy from the Sun into chemical energy (see Energy and Earth). With this discovery came the realization that phosphorus would make an even more effective fertilizer when treated with sulfuric acid, which makes it soluble, or capable of being dissolved, in water. This compound, known as superphosphate, can be produced from phosphates, a type of mineral.

Phosphates represent one of the eight major classes of mineral (see Minerals). All phosphates contain a characteristic formation, PO_4, which is bonded to other elements or compounds—for example, with aluminum in aluminum phosphate, or $AlPO_4$. Phosphorus fertilizer is typically calcium phosphate, known as bone ash, the most important industrial mineral (see Economic Geology) produced from phosphorus. Another significant phosphate is sodium phosphate, used in dishwashing detergents. In fact, phosphates once played a much larger role in the detergent industry—with disastrous consequences, as we shall see.

The phosphorus cycle. The majority of phosphorus in the earth system is located in rocks and deposits of sediment, from which it can be removed by one of three processes: weathering, the breakdown of rocks and minerals at or near the surface of Earth as the result of physical, chemical, or biological processes (see Erosion, Sediment and Sedimentation); leaching, the removal of soil materials that are in solution, or dissolved in water; and mining.

Phosphorus is highly reactive, meaning that it is likely to bond with other elements, and for this reason it often is found in compounds. Microorganisms absorb insoluble phosphorus compounds (ones that are incapable of being dissolved) and, through the action of acids within the microorganisms, turn them into soluble phosphates. Algae and other green plants absorb these phosphates and, in turn, are eaten by animals. When they die, the animals release the phosphates back into the soil.

As with all elements, the total amount of phosphorus on Earth stays constant, but the distribution of it does not. Some of the phosphorus passes from the geosphere into the biosphere, but the majority of it winds up in the ocean. It may find its way into sediments in shallow waters, in which case it continues to circulate, or it may be taken to the deep parts of the seas, in which case it is likely to be deposited for the long term.

Fish absorb particles of phosphorus, and thus some of the element returns to dry land through the catching and consumption of seafood. In addition, guano, or dung, from birds that live in an ocean environment (e.g., seagulls) also returns portions of phosphorus to the terrestrial environment. Nonetheless, geochemists



A stand of fir trees shows the devastating effects of acid rain, which is created when sulfuric acid mixes with moisture in the atmosphere. *(© Will and Demi McIntyre/Photo Researchers. Reproduced by permission.)*

believe that phosphorus is being transferred steadily to the ocean, from whence it is not likely to return. It is for this reason that phosphorus-based fertilizers are important, because they feed the soil with nutrients that otherwise would be continually lost.

EUTROPHICATION. To be sure, phosphorus, in the proper quantities, is good for the environment. But as with medicine or any other beneficial substance, if a little is good, that does not mean that a lot is necessarily better. In the case of phosphorus, an overabundance of the element in the environment can lead to a phenomenon called eutrophication, a state of heightened biological productivity in a body of water. One of the leading causes of eutrophication (from a Greek term meaning "well nourished") is a high rate of nutrient input, in the form of phosphates or nitrates, a nitrogen-oxygen compound (see Nitrogen Cycle).

As a result of soil erosion, fertilizers make their way into bodies of water, as does detergent runoff in wastewater. Excessive phosphates and nitrates stimulate growth in algae and other green plants, and when these plants die, they drift to the bottom of the lake or other body of water. There, decomposers consume the remains of the plants and, in the process, also use oxygen that otherwise would be available to fish, mollusks, and other forms of life. As a result, those species die off, to be replaced by others that are more tolerant of lowered oxygen levels—for example, worms. Needless to say, the outcome of eutrophication is devastating to the lake's ecosystem.

During the 1960s, Lake Erie—one of the Great Lakes on the U.S.-Canadian border—became an example of eutrophication gone mad. As a result of high phosphate concentrations, Erie's waters were choked with plant and algae growth. Fish were unable to live in the water, the beaches reeked with the smell of decaying algae, and Erie became widely known as a "dead" body of water. This situation led to the passage of new environmental standards and pollution controls by both the United States and Canada, whose governments acted to reduce drastically the phosphate content in fertilizers and detergents. Lake Erie proved to be an environmental success story: within a few decades the lake once again teemed with life.

Sulfur and the Sulfur Cycle

If there is any element that can be said to have a bad image—and a falsely bad one at that—it is sulfur. As everyone "knows," sulfur has a foul smell, and this smell, combined with its com-

KEY TERMS

ALCHEMY: A set of mystical beliefs based on the idea that ordinary matter can be perfected. Though it was a pseudoscience, alchemy, which flourished in the late Middle Ages, was a forerunner of scientific chemistry.

ATMOSPHERE: In general, an atmosphere is a blanket of gases surrounding a planet. Unless otherwise identified, however, the term refers to the atmosphere of Earth, which consists of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon (0.07%).

ATOMIC NUMBER: The number of protons in the nucleus of an atom. Since this number is different for each element, elements are listed on the periodic table in order of atomic number.

BIOGEOCHEMICAL CYCLES: The changes that particular elements undergo as they pass back and forth through the various earth systems and particularly between living and nonliving matter. The elements involved in biogeochemical cycles are hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur.

BIOSPHERE: A combination of all living things on Earth—plants, mammals, birds, amphibians, reptiles, aquatic life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

CARNIVORE: A meat-eating organism.

CHEMICAL BONDING: The joining through electromagnetic force of atoms that sometimes, but not always, represent more than one chemical element. The result is the formation of a molecule.

CHEMICAL SYMBOL: A one-letter or two-letter abbreviation for the name of an element.

COMPOUND: A substance made up of atoms of more than one element chemically bonded to one another.

DECOMPOSERS: Organisms that obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. The principal forms of decomposers are bacteria and fungi.

DECOMPOSITION REACTION: A chemical reaction in which a compound is broken down into simpler compounds or into its constituent elements. In the earth system, this often is achieved through the help of detritivores and decomposers.

DETRITIVORES: Organisms that feed on waste matter, breaking organic material down into inorganic substances that then can become available to the biosphere in the form of nutrients for plants. Their function is similar to that of decomposers; however, unlike decomposers—which tend to be bacteria or fungi—detritivores are relatively complex organisms, such as earthworms or maggots.

ECOSYSTEM: A term referring to a community of interdependent organisms along with the inorganic components of their environment.

ELEMENT: A substance made up of only one kind of atom. Unlike compounds, elements cannot be broken chemically into other substances.

KEY TERMS CONTINUED

EUTROPHICATION: A state of heightened biological productivity in a body of water, which is typically detrimental to the ecosystem in which it takes place. Eutrophication can be caused by an excess of nitrogen or phosphorus in the form of nitrates and phosphates, respectively.

FOOD WEB: A term describing the interaction of plants, herbivores, carnivores, omnivores, decomposers, and detritivores, each of which consumes nutrients and passes it along to other organisms.

GEOCHEMISTRY: A branch of the earth sciences, combining aspects of geology and chemistry, that is concerned with the chemical properties and processes of Earth—in particular, the abundance and interaction of chemical elements and their isotopes.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

HERBIVORE: A plant-eating organism.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

LEACHING: The removal of soil materials that are in solution, or dissolved in water.

MINERAL: A naturally occurring, typically inorganic substance with a specific chemical composition and a crystalline structure.

MIXTURE: A substance with a variable composition, meaning that it is composed of molecules or atoms of differing types. Compare with *compound.*

MOLECULE: A group of atoms, usually but not always representing more than one element, joined in a structure. Compounds typically are made up of molecules.

bustibility, led to the biblical association of *brimstone*—the ancient name for the element—with the fires of hell. It may come as a surprise, then, to learn that sulfur has no smell of its own. Only in combination with other elements does it acquire the offensive odor that has led to its unpleasant reputation.

An example of such a compound is hydrogen sulfide, a poisonous substance present in intestinal gas. The May 2001 *National Geographic* included two stories relating to the presence of natural hydrogen sulfide deposits on opposite sides of the earth, and in both cases the presence of these toxic fumes created unusual ecosystems.

A system of caves known as Villa Luz in southern Mexico contains some 20 underground springs that carry large quantities of hydrogen sulfide. Among the strange creatures that have made Villa Luz their home are species of fish colored bright red; the pigmentation is a result of the fact that they have to produce high quantities of hemoglobin (a component in red blood cells) to survive on the scant oxygen. The waters of the cave also are populated by microorganisms that oxidize the hydrogen sulfide and turn it into sulfuric acid, which dissolves the rock walls and continually enlarges the cave.

Thousands of miles away, in the Black Sea, explorers examining evidence of a great ancient flood like the one depicted in the Bible (see Earth, Science, and Nonscience) found an unexpected ally in the form of hydrogen sulfide. Because the Black Sea lacks the temperature differences that cause water to circulate from the bottom upward, hydrogen sulfide had gathered at the bottom and stayed there, covered by dense layers of saltwater. Oxygen could not reach the

KEY TERMS CONTINUED

OMNIVORE: An organism that eats both plants and other animals.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals) and oxides, such as carbon dioxide.

PERIODIC TABLE OF ELEMENTS: A chart that shows the elements arranged in order of atomic number along with their chemical symbols and the average atomic mass for each particular element.

PHOTOSYNTHESIS: The biological conversion of light energy (that is, electromagnetic energy) from the Sun to chemical energy in plants.

REACTIVITY: A term referring to the ability of one element to bond with others. The higher the reactivity, the greater the tendency to bond.

SEDIMENT: Material deposited at or near Earth's surface from a number of sources, most notably preexisting rock. There are three types of sediment: rocks, or clastic sediment; mineral deposits, or chemical sediment; and organic sediment, composed primarily of organic material.

SOLUBLE: Capable of being dissolved.

SOLUTION: A homogeneous mixture (i.e., one that is the same throughout) in which one or more substances is dissolved in another substance—for example, sugar dissolved in water.

WEATHERING: The breakdown of rocks and minerals at or near the surface of Earth due to physical, chemical, or biological processes.

bottom of the Black Sea, and thus wood-boring worms could not live in the toxic environment. As a result, a 1,500-year-old shipwreck had been virtually undisturbed.

THE SULFUR CYCLE. Sulfur is removed from rock by weathering, at which point it reacts with oxygen in the air to form sulfate, or SO_4. This sulfate is taken in by plants and microorganisms, which convert it to organic materials and pass it on to animals in the food web. Later, when these organisms die, decomposers absorb the sulfur from their bodies and return it to the environment. As with phosphorus, however, sulfur is being lost continually to the oceans as it drains through lakes and streams (and through the atmosphere) on its way to the sea.

In the ocean ecosystem, sulfur can take one of three routes. Some of it circulates through food webs, and some drifts to the bottom to bond with iron in the form of ferrous sulfide, or FeS. Ferrous sulfide contributes to the dark color of sediments at the bottom of the ocean. On the other hand, sulfur may be returned to the atmosphere, released by spray from saltwater. In addition, sulfur can pass into the atmosphere as the result of volcanic activity or through the action of bacteria, which release it in the form of hydrogen sulfide, the foul-smelling gas discussed earlier.

As with all biogeochemical cycles, humans play a part in the sulfur cycle, and the role of modern industrial society is generally less than favorable, as is true of most such cycles. A particularly potent example is the production of acid rain. Among the impurities in coal is sulfur, and when coal is burned (as it still is, for instance, in electric power plants), it results in the production of sulfur dioxide and sulfur trioxide—SO_2

and SO_3, respectively. Sulfur trioxide reacts with water in the air to produce sulfuric acid, or H_2SO_4. This mixes with moisture in the atmosphere to create acid rain, which is hazardous to both plant and animal life.

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THE CARBON CYCLE

CONCEPT

If a person were asked to name the element most important to sustaining life, chances are he or she would say oxygen. It is true that many living things depend on oxygen to survive, but, in fact, carbon is even more fundamental to the sustenance of life. Indeed, in a very real sense, carbon *is* life, since every living thing contains carbon and the term *organic* refers to certain varieties present in all life-forms. Yet carbon, in the form of such oxides as carbon dioxide as well as carbonates like calcium carbonate, is a vital part of the inorganic realm as well. Hence, the carbon cycle, by which the element is circulated through the biosphere, geosphere, atmosphere, and hydrosphere, is among the most complex of biogeochemical cycles.

HOW IT WORKS

Geochemistry

Chemistry is concerned with the composition, structure, properties, and changes of substances, including elements, compounds, and mixtures. Central to the discipline is the atomic model, or the idea that all matter is composed of atoms, each of which represents one and only one chemical element. An element thus is defined as a substance made up of only one kind of atom, which cannot be broken chemically into other substances. A chemical reaction involves either the bonding of one atom with another or the breaking of chemical bonds between atoms.

Geochemistry brings together geology and chemistry, though as the subdiscipline has matured in the period since the 1940s, its scope has widened to take in aspects of other disciplines and subdisciplines. With its focus on such issues as the recycling of elements between the various sectors of the earth system, especially between living and nonliving things, geochemistry naturally encompasses biology, botany, and a host of earth science subdisciplines, such as hydrology.

BIOGEOCHEMICAL CYCLES. Among the most significant areas of study within the realm of geochemistry are biogeochemical cycles. These are the changes that a particular element undergoes as it passes back and forth through the various earth systems—particularly between living and nonliving matter. As we shall see, this transition between the worlds of the living and the nonliving is particularly interesting where carbon is concerned.

Along with carbon, five other elements—hydrogen, nitrogen, oxygen, phosphorus, and sulfur—are involved in biogeochemical cycles. With the exception of phosphorus, which plays little part in the atmosphere, these elements move through all four earth systems, including the atmosphere, the biosphere (the sum of all living things as well as formerly living things that have not yet decomposed), the hydrosphere (Earth's water, except for water vapor in the atmosphere), and the geosphere, or the upper part of Earth's continental crust.

Earth systems and biogeochemical cycles are discussed in greater depth within essays devoted to those topics (see Earth Systems and Biogeochemical Cycles). Likewise, the nitrogen cycle is treated separately (see Nitrogen Cycle). The role of hydrogen and oxygen, which chemically bond



The name carbon comes from the Latin word for charcoal, carbo. Coal has a wide variety of uses, from manufacturing steel to generating electricity. *(© Andrew J. Martinez/Photo Researchers. Reproduced by permission.)*

to form water, is discussed in the context of the hydrosphere (see Hydrologic Cycle).

Elements and Compounds

We have referred to elements and compounds, which are essential to the study of chemistry; now let us examine them briefly before going on to the subject of a specific and very important element, carbon. An element is defined not by outward characteristics, though elements do have definable features by which they are known; rather, the true meaning of the term *element* is discernible only at the atomic level.

Every atom has a nucleus, which contains protons, or subatomic particles of positive electric charge. The identity of an element is defined by the number of protons in the nucleus: for instance, if an atom has only a single proton, by definition it must be hydrogen. An atom with six protons in the nucleus, on the other hand, is always an atom of carbon. Thus, the elements are listed on the periodic table of elements by atomic number, or the number of protons in the atomic nucleus.

Electrons and chemical reactions. While protons are essential to the definition of an element, they play no role in the bonding between atoms, which usually produces chemical compounds. (The reason for this is qualified by the modifier *usually,* in that sometimes two atoms of the same element may bond as well.) Chemical bonding involves only the electrons, which are negatively charged subatomic particles that spin around the nucleus. In fact, only certain of these fast-moving particles take part in bonding. These are the valence electrons, which occupy the highest energy levels in the atom.

One might say that valence electrons are at the "outside edge" of the atom, though the model of atomic structure, considered only in the briefest form here, is far more complex than that phrase implies. In any case, elements have characteristic valence electron patterns that affect their reactivity, or their ability to bond. Carbon is structured in such a way that it can form multiple bonds, and this feature plays a significant part in its importance as an element.

When an element reacts with another, they join together, generally in a molecule (we will examine some exceptions), to form a compound. Though the atoms themselves remain intact, and an element can be released from a compound, a

compound quite often has properties quite unlike those of the original elements. Carbon and oxygen are essential to sustaining life, but when a single atom of one bonds with a single atom of the other, they form a toxic gas, carbon monoxide. And whereas carbon in its elemental form is a black powder and hydrogen and oxygen are colorless, odorless gases, when bonded in the proper proportions and structure, the three create sugar.

Carbon

The name carbon comes from the Latin word for charcoal, *carbo.* In fact, charcoal—wood or other plant material that has been heated without enough air present to make it burn—is just one of many well-known substances that contain carbon. Others include coal, petroleum, and other fossil fuels, all of which contain hydrocarbons, or chemical compounds built around strings of carbon and hydrogen atoms. Graphite is pure carbon, and coke, a refined version of coal, is very nearly pure. Not everything made of carbon is black, however: diamonds, too, are pure carbon in another form.

Though carbon makes up only a small portion of the known elemental mass in Earth's crust, waters, and atmosphere—just 0.08%, or 1/1,250 of the whole—it is the fourteenth most abundant element on the planet. In the human body, carbon is second only to oxygen in abundance and accounts for 18% of the body's mass. Present in the inorganic rocks of the ground and in the living creatures above it, carbon is everywhere in the earth system.

CARBON BONDING. There are two elements noted for their ability to form long strings of atoms and seemingly endless varieties of molecules: one is carbon, and the other is silicon, directly below it on the periodic table. Just as carbon forms a vast array of organic compounds, silicon, found in a huge variety of minerals, is at the center of a large number of inorganic compounds. Yet carbon is capable of forming an even greater number of bonds than silicon. (For more about silicon and the silicates, see the entries Minerals and Economic Geology.)

Carbon is distinguished further by its high value of electronegativity, the relative ability of an atom to attract valence electrons. In addition, with four valence electrons, carbon is ideally suited to finding other elements (or other carbon atoms) with which to form chemical bonds. Normally, an element does not necessarily have the ability to bond with as many other elements as it has valence electrons, but carbon—with its four valence electrons—happens to be tetravalent, or capable of bonding to four other atoms at once. Additionally, carbon can form not just a single bond but also a double bond or even a triple bond with other elements.



A diamond is an allotrope, a crystalline form, of carbon. Essentially, it is a huge molecule composed of carbon atoms strung together by covalent bonds. *(© V. Fleming/Photo Researchers. Reproduced by permission.*

ALLOTROPES OF CARBON. Carbon has several allotropes—different versions of the same element distinguished by their molecular structure. The first of them is graphite, a soft material that most of us regularly encounter in the form of pencil "lead." Graphite is essentially a series of one-atom-thick sheets of carbon bonded together in a hexagonal pattern, but with only very weak attractions between adjacent sheets.

Then there is that most alluring of all carbon allotropes, diamond. Neither diamonds nor graphite, strictly speaking, are formed of molecules. Their arrangement is definite, as with a molecule, but their size is not: they simply form repeating patterns that seem to stretch on forev-

er. Whereas graphite is in the form of sheets, a diamond is basically a huge "molecule" composed of carbon atoms strung together by what are known as covalent chemical bonds.

Graphite and diamond are both crystalline—solids in which the constituent parts have a simple and definite geometric arrangement that is repeated in all directions. (All minerals are crystalline in structure. See Minerals.) A third carbon allotrope, buckminsterfullerene, discovered in 1985 and named after the American engineer and philosopher R. Buckminster Fuller (1895–1983), is also crystalline in form.

Carbon takes yet another form, distinguished from the other three allotropes in that it is amorphous in structure—lacking a definite shape—as opposed to crystalline. Though it retains some of the microscopic structures of the plant cells in the wood from which it is made, charcoal is mostly amorphous carbon. Coal and coke are particularly significant varieties of amorphous carbon. Formed by the decay of fossils, coal was the first important fossil fuel (discussed later in this essay) used to provide heat and power to human societies.

REAL-LIFE APPLICATIONS

Organic Chemistry

Organic chemistry is the study of carbon, its compounds (with the exception of the carbonates and oxides mentioned earlier), and their properties. At one time chemists thought that *organic* was synonymous with living, and even as recently as the early nineteenth century, they believed that organic substances contained a supernatural "life force." Then, in 1828, the German chemist Friedrich Wöhler (1800–1882) made an amazing discovery.

By heating a sample of ammonium cyanate, a material from a nonliving source, Wöhler converted it to urea, a waste product in the urine of mammals. As he later observed, "without benefit of a kidney, a bladder, or a dog," he had turned an inorganic substance into an organic one. It was almost as though he had created life. Actually, what he had discovered was the distinction between organic and inorganic material, which results from the way in which the carbon chains are arranged.

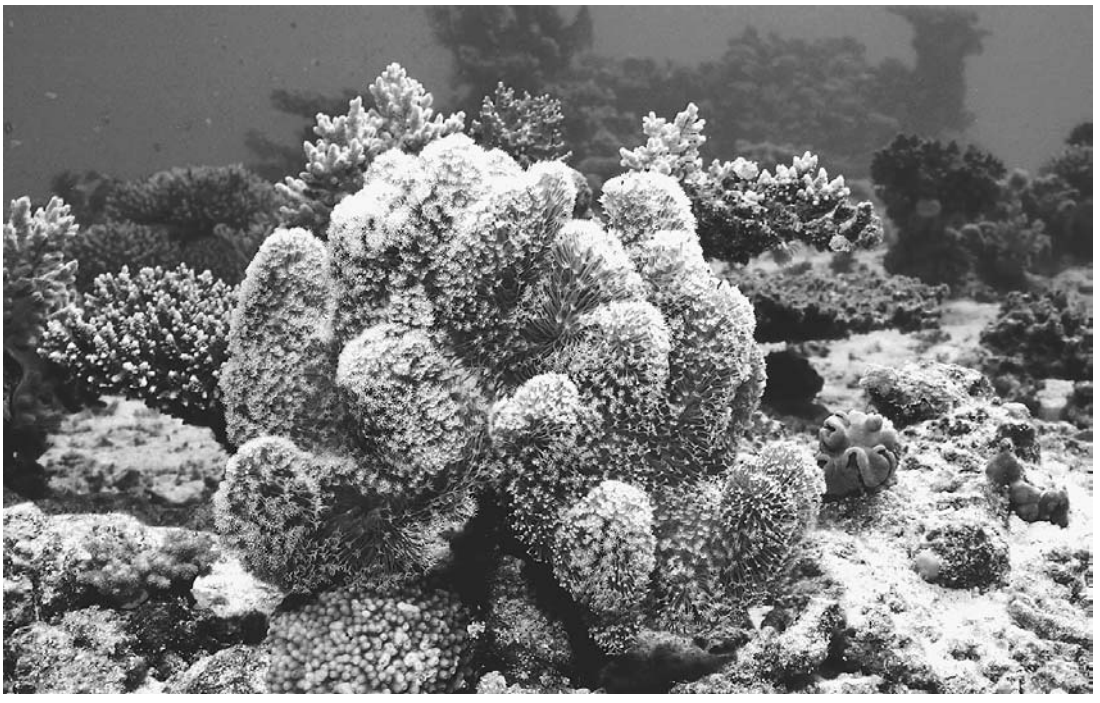
Organic chemistry encompasses the study of many things that people commonly think of as "organic"—living creatures, formerly living creatures, and the parts and products of their bodies—but it also is concerned with substances that seem quite far removed from the living world. Among these substances are rubber, vitamins, cloth, and paper, but even in these cases, it is easy to see the relationship to a formerly living organism: a rubber plant, or a tree that was cut down to make wood pulp. But it might come as a surprise to learn that plastics, which at first glance would seem completely divorced from the living world, also have an organic basis. All manner of artificial substances, such as nylon and polyester, are made from hydrocarbons.

FOSSIL FUELS. During the Mesozoic era, which began about 248.2 million years ago, dinosaurs ruled the earth; then, about 65 million years ago, a violent event brought an end to their world. The cause of this mass extinction is unknown, though it is likely that a meteorite hit the planet, sending so much dust into the atmosphere that it dramatically changed local climates, bringing about the destruction of the dinosaurs—along with a huge array of other animal and plant forms. (See Paleontology for more on this subject.)

The bodies of the dinosaurs, along with those of other organisms, were deposited in the solid earth and covered by sediment. They might well have simply rotted, and indeed many of them probably did. But many of these organisms were deposited in an anaerobic, or non-oxygen-containing, environment. Rather than simply rotting, this organic material underwent transformation into hydrocarbons and became the basis for the fossil fuels, the most important of which—from the standpoint of modern society—is petroleum. (See Economic Geology for more on this subject.)

Carbonates

Carbonates are important forms of inorganic carbon in the geosphere. In chemical terms, a carbonate is made from a single carbon atom bonded to three oxygen atoms, but in mineralogical terms, carbonates are a class of mineral that may contain carbon, nitrogen, or boron in a characteristic molecular formation. Typically, a carbonate is transparent and light in color with a relatively high density.



Calcium carbonate, one of the most common compounds in the geosphere, is found in seashells, eggshells, pearls, and coral (pictured here), bridging the boundary between the living and the nonliving. *(© Fred McConnaughey/Photo Researchers. Reproduced by permission.)*

Among carbonate minerals, the most significant compound is calcium carbonate ($CaCO_3$). One of the most common compounds in the entire geosphere, constituting 7% of the known crustal mass, it is found in such rocks as limestone, marble, and chalk. (Just as pencil "lead" is not really lead, the "chalk" used for writing on blackboards is actually gypsum, a form of calcium sulfate.) Additionally, calcium carbonate can combine with magnesium to form dolomite, and in caves it is the material that makes up stalactites and stalagmites. Yet calcium carbonate also is found in coral, seashells, eggshells, and pearls. This is a good example of how a substance can cross the chemical boundary between the worlds of the living and nonliving.

In the oceans, calcium reacts with dissolved carbon dioxide, forming calcium carbonate and sinking to the bottom. Millions of years ago, when oceans covered much of the planet, sea creatures absorbed calcium and carbon dioxide from the water, which reacted to form calcium carbonate that went into their shells and skeletons. After they died, their bodies became sedimented in the ocean floor, forming vast deposits of limestone.

Carbon Dioxide and Carbon Monoxide

Historically, carbon dioxide was the first gas to be distinguished from ordinary air, when in 1630 the Flemish chemist and physicist Jan Baptista van Helmont (1577?–1644) discovered that air was not a single element, as had been thought up to that time. The name perhaps most closely associated with carbon dioxide, however, is that of the English chemist Joseph Priestley (1733–1804), who created carbonated water, used today in making soft drinks. Not only does the gas add bubbles to drinks, it also acts as a preservative.

By Priestley's era, chemists had begun to glimpse a relationship between plant life and carbon dioxide. Up until that time, it had been believed that plants purify the air by day and poison it at night. Today we know that carbon dioxide is an essential component in the natural balance between plant and animal life. Animals, including humans, breathe in air, and, as a result of a chemical reaction in their bodies, the oxygen molecules (O_2) bond with carbon to produce carbon dioxide. Plants "breathe" in this carbon dioxide (which is as important to their survival as air is to animals), and a reverse reaction leads

KEY TERMS

AMORPHOUS: A term for a type of solid that lacks a definite shape. Compare with *crystalline.*

ATOMIC NUMBER: The number of protons in the nucleus of an atom. Since this number is different for each element, elements are listed on the periodic table in order of atomic number.

BIOGEOCHEMICAL CYCLES: The changes that particular elements undergo as they pass back and forth through the various earth systems and particularly between living and nonliving matter. The elements involved in biogeochemical cycles are hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur.

CELLULAR RESPIRATION: A process that, when it takes place in the presence of oxygen, involves the intake of organic substances, which are broken down into carbon dioxide and water, with the release of considerable energy.

CHEMICAL BONDING: The joining through electromagnetic force of atoms that sometimes, but not always, represent more than one chemical element. The result is the formation of a molecule.

COMPOUND: A substance made up of atoms of more than one element, chemically bonded to one another.

CRYSTALLINE SOLID: A type of solid in which the constituent parts have a simple and definite geometric arrangement that is repeated in all directions.

DECOMPOSERS: Organisms that obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. The principal forms of decomposer are bacteria and fungi.

DECOMPOSITION REACTION: A chemical reaction in which a compound is broken down into simpler compounds, or into its constituent elements. In the earth system, this often is achieved through the help of detritivores and decomposers.

ECOSYSTEM: A term referring to a community of interdependent organisms along with the inorganic components of their environment.

to the release of oxygen from the plants back into the atmosphere.

CARBON MONOXIDE. Priestley discovered another carbon-oxygen compound quite different from carbon dioxide: carbon monoxide. The latter is used today by industry for several purposes, such as the production of certain fuels, proving that this toxic gas can be quite beneficial when used in a controlled environment. Nonetheless, carbon monoxide produced in an uncontrolled environment—generated by the burning of petroleum in automobiles as well as by the combustion of wood, coal, and other carbon-containing fuels—is extremely hazardous to human health.

When humans ingest carbon monoxide, it bonds with iron in hemoglobin, the substance in red blood cells that transports oxygen throughout the body. In effect, carbon monoxide fools the body into thinking that it is receiving oxygenated hemoglobin, or oxyhemoglobin. Upon reaching the cells, carbon monoxide has much less tendency than oxygen to break down, and therefore it continues to circulate throughout the body. Low concentrations can cause nausea, vomiting, and other effects, while prolonged exposure to high concentrations can result in death.

THE GREENHOUSE EFFECT. Although we have referred to carbon monoxide

KEY TERMS CONTINUED

ELECTRON: A negatively charged particle in an atom, which spins around the nucleus.

ELEMENT: A substance made up of only one kind of atom. Unlike compounds, elements cannot be broken chemically into other substances.

FOSSIL FUELS: Fuel derived from deposits of organic material that have experienced decomposition and chemical alteration under conditions of high pressure. These nonrenewable forms of bioenergy include petroleum, coal, peat, natural gas, and their derivatives.

GEOCHEMISTRY: A branch of the earth sciences, combining aspects of geology and chemistry, that is concerned with the chemical properties and processes of Earth—in particular, the abundance and interaction of chemical elements and their isotopes.

HYDROCARBON: Any organic chemical compound whose molecules are made up of nothing but carbon and hydrogen atoms.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon and hydrogen, thus excluding carbonates (which are minerals) and oxides such as carbon dioxide.

PERIODIC TABLE OF ELEMENTS: A chart that shows the elements arranged in order of atomic number along with the chemical symbol and the average atomic mass for each particular element.

PHOTOSYNTHESIS: The biological conversion of light energy (that is, electromagnetic energy) from the Sun to chemical energy in plants.

PROTON: A positively charged particle in an atom.

REACTIVITY: A term referring to the ability of one element to bond with others. The higher the reactivity, the greater the tendency to bond.

VALENCE ELECTRONS: Electrons that occupy the highest principal energy level in an atom. These are the electrons involved in chemical bonding.

as toxic, it should be noted that carbon dioxide also would be toxic to a human or other animal—for instance, if one were trapped in a sealed compartment and forced to breathe in the carbon dioxide released from one's lungs. On a global scale, both carbon dioxide and carbon monoxide in the atmosphere, produced in excessive amounts by the burning of fossil fuels, pose a potentially serious threat.

Both gases are believed to contribute to the greenhouse effect, which, as discussed in Energy and Earth, is a mechanism by which the planet efficiently uses the heat it receives from the Sun. Human consumption of fossil fuels and use of other products, including chlorofluorocarbons in aerosol cans, however, has produced a much greater quantity of greenhouse gases than the atmosphere needs to maintain normal heat levels. As a result, some scientists believe, buildup of greenhouse gases in the atmosphere is causing global warming.

CELLULAR RESPIRATION

The burning of fossil fuels is one of three ways that carbon enters the atmosphere, the others being volcanic eruption and cellular respiration. When cellular respiration takes place in the presence of oxygen, there is an intake of organic substances, which are broken down into carbon

dioxide and water, with the release of considerable energy.

When plants take in carbon dioxide from the atmosphere, they combine it with water and manufacture organic compounds, using energy they have trapped from sunlight by means of photosynthesis—the conversion of light to chemical energy through biological means. As a by-product of photosynthesis, plants release oxygen into the atmosphere, as we have noted earlier.

In the process of photosynthesis, plants produce carbohydrates, which are various compounds of carbon, hydrogen, and oxygen that are essential to life. (The other two fundamental components of a diet are fats and proteins, both of which are carbon-based as well.) Animals eat the plants or eat other animals that eat the plants and thus incorporate the fats, proteins, and sugars (a form of carbohydrate) from the plants into their bodies. In cellular respiration, these nutrients are broken down to create carbon dioxide.

DECOMPOSITION. Cellular respiration also releases carbon into the atmosphere through the action of decomposers, organisms that obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. Bacteria and fungi, the principal forms of decomposer, extract energy contained in the chemical bonds of the organic matter they are decomposing and, in the process, release carbon dioxide.

Certain ecosystems, or communities of interdependent organisms, are better than others at producing carbon dioxide through decomposition. As one would expect, environments where heat and moisture are greatest—for example, a tropical rainforest—yield the fastest rates of decomposition. On the other hand, decomposition proceeds much more slowly in dry, cold climates such as that of a subarctic tundra.

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THE NITROGEN CYCLE

CONCEPT

Contrary to popular belief, the air we breathe is not primarily oxygen; by far the greatest portion of air is composed of nitrogen. A colorless, odorless gas noted for its lack of chemical reactivity—that is, its tendency not to bond with other elements—nitrogen plays a highly significant role within the earth system. Both through the action of lightning in the sky and of bacteria in the soil, nitrogen is converted to nitrites and nitrates, compounds of nitrogen and oxygen that are then absorbed by plants to form plant proteins. The latter convert to animal proteins in the bodies of animals who eat the plants, and when an animal dies, the proteins are returned to the soil. Denitrifying bacteria break down these compounds, returning elemental nitrogen to the atmosphere.

HOW IT WORKS

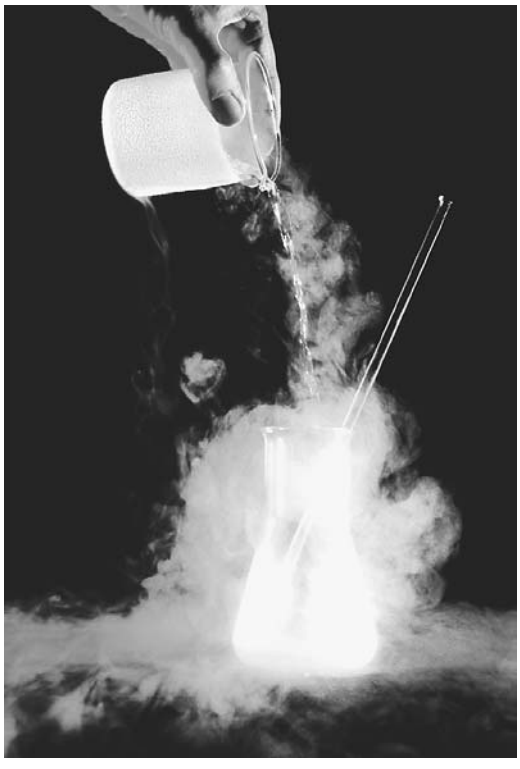
Chemistry and Elements

The concepts we discuss in this essay fall under the larger heading of geochemistry. A branch of the earth sciences that combines aspects of geology and chemistry, geochemistry is concerned with the chemical properties and processes of Earth. Among particular areas of interest in geochemistry are biogeochemical cycles, or the changes that particular elements undergo as they pass back and forth through the various earth systems and particularly between living and nonliving matter. The elements involved in biogeochemical cycles are hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur (see Biogeochemical Cycles and Carbon Cycle).

An element is a substance composed of a single type of atom, which cannot be broken down chemically into a simpler substance. Each element is distinguished by its atomic number, or the number of protons (positively charged subatomic particles) in the nucleus, or center, of the atom. On the periodic table of elements, these fundamental substances of the universe are listed in order of atomic number, from hydrogen to uranium—which has the highest atomic number (92) of any element that occurs in nature—and beyond. The elements with an atomic number higher than that of uranium, all of which have been created artificially, play virtually no role in the chemical environment of Earth and are primarily of interest only to specialists in certain fields of chemistry and physics.

Everything that exists in the universe is an element, a compound formed by the chemical bonding of elements, or a mixture of compounds. In order to bond and form a compound, elements experience chemical reactions, which are the result of attractions on the part of electrons (negatively charged subatomic particles) that occupy the highest energy levels in the atom. These electrons are known as valence electrons.

CHEMICAL CHANGES. A chemical change is a phenomenon quite different from a physical change. If liquid water boils or freezes (both of which are examples of a physical change resulting from physical processes), it is still water. Physical changes do not affect the internal composition of an item or items; a chemical change, on the other hand, occurs when the actual composition changes—that is, when one substance is transformed into another. Chemical change requires a chemical reaction, a process whereby



LIQUID NITROGEN. *(© David Taylor/Photo Researchers. Reproduced by permission.)*

the chemical properties of a substance are altered by a rearrangement of atoms.

There are several clues that tell us when a chemical reaction has taken place. In many chemical reactions, for instance, the substance may experience a change of state or phase—as, for instance, when liquid water is subjected to an electric current through a process known as *electrolysis,* which separates it into oxygen and hydrogen, both of which are gases. Another clue that a chemical reaction has occurred is a change of temperature. Unlike the physical change of liquid water to ice or steam, however, this temperature change involves an alteration of the chemical properties of the substances themselves. Chemical reactions also may encompass changes in color, taste, or smell.

NITROGEN'S PLACE AMONG THE ELEMENTS

With an atomic number of 7, nitrogen (chemical symbol N) is one of just 19 elements that are nonmetals. Unlike metals, nonmetals are poor conductors of heat and electricity and are not ductile—in other words, they cannot be reshaped easily. The vast majority of elements are metallic, however, the only exceptions being the nonmetals as well as six "metalloids," or elements that display characteristics of both metals and nonmetals.

Nitrogen is also one of eight "orphan" nonmetals—those nonmetals that do not belong to any family of elements, such as the halogens or noble gases. All six of the elements involved in biogeochemical cycles, in fact, are "orphan" nonmetals, with boron and selenium rounding out the list of eight orphans. Sometimes nitrogen is considered the head of a "family" of elements, all of which occupy a column or group on the periodic table.

These five elements—nitrogen, phosphorus, arsenic, antimony, and bismuth—share a common pattern of valence electrons, but otherwise they share little in terms of physical properties or chemical behavior. By contrast, chemicals that truly are related all have a common "family resemblance": all halogens are highly reactive, for instance, while all noble gases are extremely unreactive.

ABUNDANCE. The seventeenth most abundant element on Earth, nitrogen accounts for 0.03% of the planet's known elemental mass. This may seem very small, but at least nitrogen is among the 18 elements considered relatively abundant. These 18 elements account for all but 0.49% of the planet's known elemental mass, the remainder being composed of numerous other elements in small quantities. The term known elemental mass takes account of the fact that scientists do not know with certainty the elemental composition of Earth's interior, though it likely contains large proportions of iron and nickel. The known mass, therefore, is that which exists from the bottom of the crust to the top layers of the atmosphere.

Elemental proportions too small to be measured in percentage points are rendered in parts per million (ppm) or even parts per billion (ppb). Within the crust itself, nitrogen's share is certainly modest: a concentration of 19 ppm, which ties it with gallium, a metal whose name is hardly a household word, for a rank of thirty-third. On the other hand, this still makes it more abundant in the crust than many quite familiar metals, including lithium, uranium, tungsten, silver, mercury, and platinum.

In Earth's atmosphere, on the other hand, the proportion of nitrogen is much, much high-

er. The atmosphere is 78% nitrogen and 21% oxygen, while the noble gas argon accounts for 0.93%. The remaining 0.07% is taken up by various trace gases, including water vapor, carbon dioxide, and ozone, or O_3.

In the human body, nitrogen's share is much more modest than it is in the atmosphere but still 10 times greater than it is in relation to the planet's total mass. The element accounts for 3% of the body's mass, making it the fourth most abundant element in the human organism.

Properties and Applications of Nitrogen

The Scottish chemist Daniel Rutherford (1749–1819) usually is given credit for discovering nitrogen in 1772, when he identified it as the element that remained when oxygen was removed from air. Several other scientists at about the same time made a similar discovery.

Because of its heavy presence in air, nitrogen is obtained primarily by cooling air to temperatures below the boiling points of its major components. Nitrogen boils (that is, turns into a gas) at a lower temperature than oxygen: –320.44°F (–195.8°C), as opposed to –297.4°F (–183°C). If air is cooled to –328°F (–200°C), thus solidifying it, and then allowed to warm slowly, the nitrogen boils first and therefore evaporates first. The nitrogen gas is captured, cooled, and liquefied once more.

Nitrogen also can be obtained from such compounds as potassium nitrate or saltpeter, found primarily in India, or from sodium nitrate (Chilean saltpeter), which comes from the desert regions of Chile. To isolate nitrogen chemically, various processes are undertaken in a laboratory—for instance, heating barium azide or sodium azide, both of which contain nitrogen.

REACTIONS WITH OTHER ELEMENTS. Rather than appearing as single atoms, nitrogen is diatomic, meaning that two nitrogen atoms typically bond with each other to form dinitrogen, or N_2. Nor do these atoms form single chemical bonds, as is characteristic of most elements; theirs is a *triple* bond, which effectively ties up the atoms' valence electrons, making nitrogen an unreactive element at relatively low temperatures.

Even at the temperature of combustion, a burning substance reacts with the oxygen in the air but not with the nitrogen. At very high temperatures, on the other hand, nitrogen combines with other elements, reacting with metals to form nitrides, with hydrogen to form ammonia, with O_2 (oxygen as it usually appears in nature, two atoms bonded in a molecule) to form nitrites, and with O_3 (ozone) to form nitrates. With the exception of the first-named group, all of these elements are important to our discussion of nitrogen.



NITROGEN COMBINES WITH HYDROGEN TO FORM AMMONIA. AMMONIUM NITRATE, A FERTILIZER, IS ALSO A DANGEROUS EXPLOSIVE. IT WAS USED IN APRIL OF 1995 TO BLOW UP THE ALFRED P. MURRAH FEDERAL BUILDING IN OKLAHOMA CITY, KILLING 168 PEOPLE. *(© James H. Robinson/Photo Researchers. Reproduced by permission.)*

SOME USES FOR NITROGEN. In processing iron or steel, which forms undesirable oxides if exposed to oxygen, a blanket of nitrogen is applied to prevent this reaction. The same principle is applied in making computer chips and even in processing foods, since these items, too, are affected detrimentally by oxidation. Because it is far less combustible than air (magnesium is one of the few elements that burns nitrogen in combustion), nitrogen also is used to clean tanks that have carried petroleum or other combustible materials.

As noted, nitrogen combines with hydrogen to form ammonia, used in fertilizers and cleaning materials. Ammonium nitrate, applied primarily as a fertilizer, is also a dangerous explosive, as shown with horrifying effect in the bombing of the Alfred P. Murrah Federal Building in Oklahoma City on April 19, 1995—a tragedy that took 168 lives. Nor is ammonium nitrate the only nitrogen-based explosive. Nitric acid is used in making trinitrotoluene (TNT), nitroglycerin, and dynamite as well as gunpowder and smokeless powder.

Introduction to the Nitrogen Cycle

The nitrogen cycle is the process whereby nitrogen passes from the atmosphere into living things and ultimately back into the atmosphere. In the process, it is converted to nitrates and nitrites, compounds of nitrogen and oxygen that are absorbed by plants in the process of forming plant proteins. These plant proteins, in turn, are converted to animal proteins in the bodies of animals who eat the plants, and when the animal dies, the proteins are returned to the soil. Denitrifying bacteria break down these organic compounds, returning elemental nitrogen to the atmosphere.

Note what happens in the nitrogen cycle and, indeed, in all biogeochemical cycles: organic material is converted to inorganic material through various processes, and inorganic material absorbed by living organisms eventually is turned into organic material. In effect, the element passes back and forth between the realms of the living and the nonliving. This may sound a bit mystical, but it is not. To be organic, a substance must be built around carbon in certain characteristic chemical structures, and by inducing the proper chemical reaction, it is possible to break down or build up these structures, thus turning an organic substance into an inorganic one, or vice versa. (For more on this subject, see Carbon Cycle.)

STEPS IN THE CYCLE. Plants depend on biologically useful forms of nitrogen, the availability of which greatly affects their health, abundance, and productivity. This is particularly the case where plants in a saltwater ecosystem (a community of interdependent organisms) are concerned. Regardless of the specific ecosystem, however, fertilization of the soil with nitrogen has an enormous impact on the growth yield of plant life, which can be critical in the case of crops. Therefore, nitrogen is by far the most commonly applied nutrient in an agricultural setting.

There are several means by which plants receive nitrogen. They may absorb it as nitrate or ammonium, dissolved in saltwater and taken up through the roots, or as various nitrogen oxide gases. In certain situations, plants have a symbiotic, or mutually beneficial, relationship with microorganisms capable of "fixing" atmospheric dinitrogen into ammonia. In any case, plants receive nitrogen and later, when they are eaten by animals, pass these nutrients along the food chain—or rather, to use a term more favored in the earth and biological sciences, the food web.

When herbivorous or omnivorous animals consume nitrogen-containing plants, their bodies take in the nitrogen and metabolize it, breaking it down to generate biochemicals, or chemicals essential to life processes. At some point, the animal dies, and its body experiences decomposition through the activity of bacteria and other decomposers. These microorganisms, along with detritivores such as earthworms, convert nitrates and nitrites from organic sources into elemental nitrogen, which ultimately reenters the atmosphere.

REAL-LIFE APPLICATIONS

Important Forms of Nitrogen

As noted earlier, dinitrogen, or N_2, is the form in which nitrogen typically appears when uncombined with other elements. This is also the form of nitrogen in the atmosphere, but it is so chemically unreactive that unlike oxygen, it plays little actual part in sustaining life. Indeed, because nitrogen in the air is essentially "filler" as far as humans are concerned, it can be substituted with helium, as is done in air tanks for divers. This prevents them from experiencing decompression sickness, or "the bends," which occurs when the diver returns too quickly to the surface, causing nitrogen in the blood to boil.

The dinitrogen in the air is a holdover from long ago in Earth's development, when volcanoes expelled elements from deep in the planet's interior to its atmosphere. Owing to its lack of reac-



Smog blankets Los Angeles in a haze. Nitric oxide reacts with oxygen in the air to form nitrogen oxide, a reddish brown gas that colors smog. *(Photograph by Walter A. Lyons. FMA Productions. Reproduced by permission.)*

tivity, dinitrogen never went anywhere. For it to play a role in the functioning of Earth cycles, it must be "fixed," as discussed later in this essay. In addition to dinitrogen, nitrogen appears in a number of other important inorganic compounds, including nitrite and nitrate; ammonia and ammonium; and nitric oxide, nitrogen dioxide, and nitrous oxide.

Nitrite and nitrate are two ionic forms of nitrogen. An ion is an atom or group of atoms that has lost or gained electrons, thus acquiring a net electric charge. Both nitrite and nitrate are anions, or negatively charged ions, designated by the use of superscript minus signs that indicate that each has a net charge of negative 1. Thus, nitrite, in which nitrogen is chemically bonded with two atoms of oxygen, is rendered as NO_2^-, while the formula for nitrate (nitrogen with three oxygen atoms), is designated as NO_3^-.

AMMONIA AND AMMONIUM. Nitrification is a process in which nitrite is produced, whereupon it undergoes a chemical reaction to form nitrate, the principal form of nitrogen nutrition for most plant species. The chemical from which the nitrite is created in the nitrification reaction is ammonium (NH_4^+), which is formed by the addition of a hydrogen cation, or a positively charged ion (H^+), to ammonia, or NH_3. The latter, which is probably familiar to most people in the form of a household cleaner, is actually an extremely abundant compound, both in natural and artificial forms.

Ammonium is soluble, or capable of being dissolved, in water and often is used as a fertilizer. It is attracted to negatively charged surfaces of clays and organic matter in soil and therefore tends to become stuck in one place rather than moving around, as nitrate does. In acidic soils, typically plants receive their nitrogen from ammonium, but most nonacidic soils can use only nitrate. As noted earlier, ammonium may be combined with nitrate to form ammonium nitrate—both a powerful fertilizer and a powerful explosive.

OXIDES. Nitrogen reenters the atmosphere in the form of the gas nitric oxide (NO), emitted primarily as the result of combustion reactions. This may occur in one of two ways. Organic nitrogen in bioenergy sources, such as biomass (organisms, their waste products, and their incompletely decomposed remains) or fossil fuels (e.g., coal or oil), may be oxidized. The latter term means that a substance undergoes a chemical reaction with oxygen: combustion itself, which requires the presence of oxygen, is an example of oxidation.

KEY TERMS

ATOM: The smallest particle of an element, consisting of protons, neutrons, and electrons. An atom can exist either alone or in combination with other atoms in a molecule.

ATOMIC NUMBER: The number of protons in the nucleus of an atom. Since this number is different for each element, elements are listed on the periodic table in order of atomic number.

BIOENERGY: Energy derived from biological sources that are used directly as fuel (as opposed to food, which becomes fuel).

BIOGEOCHEMICAL CYCLES: The changes that particular elements undergo as they pass back and forth through the various earth systems and specifically between living and nonliving matter. The elements involved in biogeochemical cycles are hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur.

CHEMICAL BONDING: The joining, through electromagnetic force, of atoms that sometimes, but not always, represent more than one chemical element. The result is usually the formation of a molecule.

COMPOUND: A substance made up of atoms of more than one element chemically bonded to one another.

DECOMPOSERS: Organisms that obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. The principal forms of decomposer are bacteria and fungi.

DECOMPOSITION REACTION: A chemical reaction in which a compound is broken down into simpler compounds or into its constituent elements. In the earth system, this often is achieved through the help of detritivores and decomposers.

DETRITIVORES: Organisms that feed on waste matter, breaking organic material down into inorganic substances that then become available to the biosphere in the form of nutrients for plants. Their function is similar to that of decomposers; however, unlike decomposers—which tend to be bacteria or fungi—detritivores are relatively complex organisms, such as earthworms or maggots.

DIATOMIC: A term describing a chemical element that typically exists as molecules composed of two atoms. Nitrogen and oxygen are both diatomic.

ECOSYSTEM: A term referring to a community of interdependent organisms along with the inorganic components of their environment.

On the other hand, nitric oxide may enter the atmosphere when atmospheric dinitrogen is combined with oxygen under conditions of high temperature and pressure, as, for instance, in an internal-combustion engine. In the atmosphere, nitric oxide reacts readily with oxygen in the air to form nitrogen dioxide (NO_2), a reddish-brown gas that adds to the tan color of smog over major cities.

Yet nitric oxide and nitrogen dioxide, usually designated together as NO_x, are also part of the life-preserving nitrogen cycle. Gaseous NO_x is taken in by plants, or oxidized to make nitrate, and circulated through the biosphere or else cycled directly to the atmosphere. In addition, denitrification, discussed later in this essay, transports nitrous oxide (N_2O) into the atmosphere from nitrate-rich soils.

KEY TERMS

ELECTRON: A negatively charged particle in an atom, which spins around the nucleus.

ELEMENT: A substance made up of only one kind of atom. Unlike compounds, elements cannot be chemically broken into other substances.

EUTROPHICATION: A state of heightened biological productivity in a body of water, which is typically detrimental to the ecosystem in which it takes place. Eutrophication can be caused by an excess of nitrogen or phosphorus in the form of nitrates and phosphates, respectively.

FOOD WEB: A term describing the interaction of plants, herbivores, carnivores, omnivores, decomposers, and detritivores, each of which consumes nutrients and passes it along to other organisms.

GEOCHEMISTRY: A branch of the earth sciences combining aspects of geology and chemistry, that is, concerned with the chemical properties and processes of Earth—in particular, the abundance and interaction of chemical elements and their isotopes.

ION: An atom or group of atoms that has lost or gained one or more electrons and thus has a net electric charge. Positively charged ions are called *cations,* and negatively charged ones are called *anions.*

LEACHING: The removal of soil materials that are in solution, or dissolved in water.

MOLECULE: A group of atoms, usually but not always representing more than one element, joined in a structure. Compounds are typically made up of molecules.

PERIODIC TABLE OF ELEMENTS: A chart that shows the elements arranged in order of atomic number along with their chemical symbols and the average atomic mass for each particular element.

PROTON: A positively charged particle in an atom.

REACTIVITY: A term referring to the ability of one element to bond with others. The higher the reactivity, the greater the tendency to bond.

SOLUBLE: Capable of being dissolved.

VALENCE ELECTRONS: Electrons that occupy the highest principal energy level in an atom. These are the electrons involved in chemical bonding.

NITROGEN PROCESSES

In order for most organisms to make use of atmospheric dinitrogen, it must be "fixed" into inorganic forms that a plant can take in through its roots and leaves. Nonbiological processes, such as a lightning strike, can bring about dinitrogen fixation. The high temperatures and pressures associated with lightning lead to the chemical bonding of atmospheric nitrogen and oxygen (both of which appear in diatomic form) to create two molecules of nitric oxide.

More often than not, however, dinitrogen fixation comes about through biological processes. Microorganisms are able to synthesize an enzyme that breaks the triple bonds in dinitrogen, resulting in the formation of two molecules

of ammonia for every dinitrogen molecule thus reacted. This effect is achieved most commonly by bacteria or algae in wet or moist environments that offer nutrients other than nitrate or ammonium. In some instances, plants enjoy a symbiotic, or mutually beneficial, relationship with microorganisms capable of fixing dinitrogen.

AMMONIFICATION, NITRIFICATION, AND DENITRIFICATION. Dinitrogen fixation is just one example of a process whereby nitrogen is processed through one or more earth systems. Another is ammonification, or the process whereby nitrogen in organisms is recycled after their death. Enabled by microorganisms that act as decomposers, ammonification results in the production of either ammonia or ammonium. Thus, the soil is fertilized by the decayed matter of formerly living things.

Ammonium, as we noted earlier, also plays a part in nitrification, a process in which it first is oxidized to produce nitrite. Then the nitrite is oxidized to become nitrate, which fertilizes the soil. As previously mentioned, nitrate is useful as a fertilizer only in non-acidic soils; acidic ones, by contrast, require ammonium fertilizer.

In contrast to nitrification is denitrification, in which nitrate is reduced to the form of either nitrous oxide or dinitrogen. This takes place under anaerobic conditions—that is, in the absence of oxygen—and on the largest scale when concentrations of nitrate are highest. Flooded fields, for example, may experience high rates of denitrification.

The Role of Humans

Humans are involved in the nitrogen cycle in several ways, not all of them beneficial. One of the most significant roles people play in the nitrogen cycle is by the introduction of nitrogen-containing fertilizers to the soil. Because nitrogen has a powerful impact on plant growth, farmers are tempted to add more and more nitrate or ammonium or both to their crops, to the point that the soil becomes saturated with it and therefore unable to absorb more.

When the soil has taken in all the nitrogen it can hold, a process of leaching—the removal of soil materials dissolved in water—eventually takes place. Nitrate, in particular, leaches from agricultural sites into groundwater as well as streams and other forms of surface water. This can lead to eutrophication, a state of heightened biological productivity that is ultimately detrimental to the ecosystem surrounding a lake or other body of water. (See Biogeochemical Cycles for more about eutrophication.)

Yet another problem associated with overly nitrate-rich soils is an excessive rate of denitrification. This happens when soils that have been loaded down with nitrates become wet for long periods of time, leading to a dramatic increase in the denitrification rate. As a result, fixed nitrogen is lost, and nitrous oxide is emitted to the air. In the atmosphere nitrous oxide may contribute to the greenhouse effect, possibly helping increase the overall temperature of the planet (see Carbon Cycle and Energy and Earth).

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THE BIOSPHERE

ECOSYSTEMS

ECOLOGY AND ECOLOGICAL STRESS

ECOSYSTEMS

CONCEPT

An ecosystem is a complete community of living organisms and the nonliving materials of their surroundings. Thus, its components include plants, animals, and microorganisms; soil, rocks, and minerals; as well as surrounding water sources and the local atmosphere. The size of ecosystems varies tremendously. An ecosystem could be an entire rain forest, covering a geographical area larger than many nations, or it could be a puddle or a backyard garden. Even the body of an animal could be considered an ecosystem, since it is home to numerous microorganisms. On a much larger scale, the history of various human societies provides an instructive illustration as to the ways that ecosystems have influenced civilizations.

HOW IT WORKS

The Biosphere

Earth itself could be considered a massive ecosystem, in which the living and nonliving worlds interact through four major subsystems: the atmosphere, hydrosphere (all the planet's waters, except for moisture in the atmosphere), geosphere (the soil and the extreme upper portion of the continental crust), and biosphere. The biosphere includes all living things: plants (from algae and lichen to shrubs and trees), mammals, birds, reptiles, amphibians, aquatic life, insects, and all manner of microscopic forms, including bacteria and viruses. In addition, the biosphere draws together all formerly living things that have not yet decomposed.

Several characteristics unite the biosphere. One is the obvious fact that everything in it is either living or recently living. Then there are the food webs that connect organisms on the basis of energy flow from one species to another. A food web is similar to the more familiar concept food chain, but in scientific terms a food chain—a series of singular organisms in which each plant or animal depends on the organism that precedes or follows it—does not exist. Instead, the feeding relationships between organisms in the real world are much more complex and are best described as a web rather than a chain.

Food Webs

Food webs are built around the flow of energy between organisms, known as energy transfer, which begins with plant life. Plants absorb energy in two ways. From the Sun, they receive electromagnetic energy in the form of visible light and invisible infrared waves, which they convert to chemical energy through a process known as photosynthesis. In addition, plants take in nutrients from the soil, which contain energy in the forms of various chemical compounds. These compounds may be organic, which typically means that they came from living things, though, in fact, the term *organic* refers strictly to characteristic carbon-based chemical structures. Plants also receive inorganic compounds from minerals in the soil. (See Minerals. For more about the role of carbon in inorganic compounds, see Carbon Cycle.)

Contained in these minerals are six chemical elements essential to the sustenance of life on planet Earth: hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur. These are the ele-

ments involved in biogeochemical cycles, through which they continually are circulated between the living and nonliving worlds—that is, between organisms, on the one hand, and the inorganic realms of rocks, minerals, water, and air, on the other (see Biogeochemical Cycles).

FROM PLANTS TO CARNIVORES. As plants take up nutrients from the soil, they convert them into other forms, which provide usable energy to organisms who eat the plants. (An example of this conversion process is cellular respiration, discussed in Carbon Cycle.) When an herbivore, or plant-eating organism, eats the plant, it incorporates this energy.

Chances are strong that the herbivore will be eaten either by a carnivore, a meat-eating organism, or by an omnivore, an organism that consumes both herbs and herbivores—that is, both plants and animals. Few animals consume carnivores or omnivores, at least by hunting and killing them. (Detritivores and decomposers, which we discuss presently, consume the remains of all creatures, including carnivores and omnivores.) Humans are an example of omnivores, but they are far from the only omnivorous creatures. Many bird species, for instance, are omnivorous.

As nutrients pass from plant to herbivore to carnivore, the total amount of energy in them decreases. This is dictated by the second law of thermodynamics (see Energy and Earth), which shows that energy transfers cannot be perfectly efficient. Energy is not "lost"—the total amount of energy in the universe remains fixed, though it may vary with a particular system, such as an individual ecosystem—but it is dissipated, or directed into areas that do not aid in the transfer of energy between organisms. What this means for the food web is that each successive level contains less energy than the levels that precede it.

DETRITIVORES AND DECOMPOSERS. In the case of a food web, something interesting happens with regard to energy efficiency as soon as we pass beyond carnivores and omnivores to the next level. It might seem at first that there could be no level beyond carnivores or omnivores, since they appear to be "at the top of the food chain," but this only illustrates why the idea of a food web is much more useful. After carnivores and omnivores, which include some of the largest, most powerful, and most intelligent creatures, come the lowliest of all organisms: decomposers and detritivores, an integral part of the food web.

Decomposers, which include bacteria and fungi, obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. Detritivores perform a similar function: by feeding on waste matter, they break organic material down into inorganic substances that then can become available to the biosphere in the form of nutrients for plants. The principal difference between detritivores and decomposers is that the former are relatively complex organisms, such as earthworms or maggots.

Both decomposers and detritivores aid in decomposition, a chemical reaction in which a compound is broken down into simpler compounds or into its constituent elements. Often an element such as nitrogen appears in forms that are not readily usable by organisms, and therefore such elements (which may appear individually or in compounds) need to be chemically processed through the body of a decomposer or detritivore. This processing involves chemical reactions in which the substance—whether an element or compound—is transformed into a more usable version.

By processing chemical compounds from the air, water, and geosphere, decomposers and detritivores deposit nutrients in the soil. These creatures feed on plant life, thus making possible the cycle we have described. Clearly this system, of which we have sketched only the most basic outlines, is an extraordinarily complex and well-organized one, in which every organism plays a specific role. In fact, earth scientists working in the realm of biosphere studies use the term niche to describe the role that a particular organism plays in its community. (For more about the interaction of species in a biological community, see Ecology and Ecological Stress.)

REAL-LIFE APPLICATIONS

The Fate of Human Civilizations

An interesting place to start in investigating examples of ecosystems is with a species near and dear to all of us: *Homo sapiens.* Much has been written about the negative effect industrial civi-

lization has, or may have, on the natural environment—a topic discussed in Ecology and Ecological Stress—but here our concern is somewhat different. What do ecosystems, and specifically the availability of certain plants and animals, teach us about specific societies?

In his 1997 bestseller *Guns, Germs, and Steel: The Fate of Human Societies,* the ethnobotanist Jared M. Diamond (1937-) explained how he came to approach this question. While he was working with native peoples in New Guinea, a young man asked him why the societies of the West enjoyed an abundance of material wealth and comforts while those of New Guinea had so little. It was a simple question, but the answer was not obvious.

Diamond refused to give any of the usual pat responses offered in the past—for example, the Marxist or socialist claim that the West prospers at the expense of native peoples. Nor, of course, could he accept the standard answer that a white descendant of Europeans might have given a century earlier, that white Westerners are smarter than dark-skinned peoples. Instead, he approached it as a question of environment, and the result was his thought-provoking analysis contained in *Guns, Germs, and Steel.*

ADVANTAGES OF GEOGRAPHY. As Diamond showed, those places where agriculture was first born were precisely those blessed with favorable climate, soil, and indigenous plant and animal life. Incidentally, none of these locales was European, nor were any of the peoples inhabiting them "white." Agriculture came into existence in four places during a period from about 8000 to 6000 B.C. In roughly chronological order, they were Mesopotamia, Egypt, India, and China. All were destined to emerge as civilizations, complete with written language, cities, and organized governments, between about 3000 and 2000 B.C.

Of course, it is no accident that civilization was born first in those societies that first developed agriculture: before a civilization can evolve, a society must become settled, and in order for that to happen, it must develop agriculture. Each of these societies, it should be noted, formed along a river, and that of Mesopotamia was born at the confluence of *two* rivers, the Tigris and Euphrates. No wonder, then, that the spot where these two rivers met was identified in the Bible as the site for the Garden of Eden or that historians today refer to ancient Mesopotamia as "the Fertile Crescent." (For a very brief analysis regarding possible reasons why modern Mesopotamia—that is, Iraq—does not fit this description, see the discussion of desertification in Soil Conservation.)

In the New World, by contrast, agriculture appeared much later and in a much more circumscribed way. The same was true of Africa and the Pacific Islands. In seeking the reasons for why this happened, Diamond noted a number of factors, including geography. The agricultural areas of the Old World were stretched across a wide area at similar latitudes. This meant that the climates were not significantly different and would support agricultural exchanges, such as the spread of wheat and other crops from one region or ecosystem to another. By contrast, the land masses of the New World or Africa have a much greater north-south distance than they do east to west.

DIVERSITY OF SPECIES. Today such places as the American Midwest support abundant agriculture, and one might wonder why that was not the case in the centuries before Europeans arrived. The reason is simple but subtle, and it has nothing to do with Europeans' "superiority" over Native Americans. The fact is that the native North American ecosystems enjoyed far less biological diversity, or biodiversity, than their counterparts in the Old World. Peoples of the New World successfully domesticated corn and potatoes, because those were available to them. But they could not domesticate emmer wheat, the variety used for making bread, when they had no access to that species, which originated in Mesopotamia and spread throughout the Old World.

Similarly, the New World possessed few animals that could be domesticated either for food or labor. A number of Indian tribes domesticated some types of birds and other creatures for food, but the only animal ever adapted for labor was the llama. The llama, a cousin of the camel found in South America, is too small to carry heavy loads. Why did the Native Americans never harness the power of cows, oxen, or horses? For the simple reason that these species were not found in the Americas. After horses in the New World went extinct at some point during the last Ice Age (see Paleontology), they did not reappear in the



The llama was one of the few domesticated animals adapted for work in the New World, a place with a small number of animal and plant species and lack of ecological complexity before the Europeans arrived in about 1500 A.D. *(© Francois Gohier/Photo Researchers. Reproduced by permission.)*

Americas until Europeans brought them after A.D. 1500.

Diamond also noted the link between biodiversity and the practice, common among peoples in New Guinea and other remote parts of the world, of eating what Westerners would consider strange cuisine: caterpillars, insects—even, in some cases, human flesh. At one time, such practices served only to brand these native peoples further as "savages" in the eyes of Europeans and their descendants, but it turns out that there is a method to the apparent madness. In places such as the highlands of New Guinea, a scarcity of animal protein sources compels people to seek protein wherever they can find it.

By contrast, from ancient times the Fertile Crescent possessed an extraordinary diversity of animal life. Among the creatures present in that region (the term sometimes is used to include Egypt as well as Mesopotamia) were sheep, goats, cattle, pigs, and horses. With the help of these animals for both food and labor—people ate horses long before they discovered their greater value as a mode of transportation—the lands of the Old World were in a position to progress far beyond their counterparts in the New.

GREATER EXPOSURE TO MICROORGANISMS. Ultimately, these societies came to dominate their physical environments and excel in the development of technology; hence the "steel" and "guns" in Diamond's title. But what about "germs"? It is a fact that after Europeans began arriving in the New World, they killed vast populations without firing a shot, thanks to the microbes they carried with them. Of course, it would be centuries before scientists discovered the existence of microorganisms. But even in 1500, it was clear that the native peoples of the New World had no natural resistance to smallpox or a host of other diseases, including measles, chicken pox, influenza, typhoid fever, and bubonic plague.

Once again the Europeans' advantage over the Native Americans derived from the ecological complexity of their world compared with that of the Indians. In the Old World, close contact with farm animals exposed humans to germs and disease. So, too, did close contact with other people in crowded, filthy cities. This exposure, of course, killed off large numbers of people, but those who survived tended to be much hardier and possessed much stronger immune systems. Therefore, when Europeans came into contact with



With its sauna-like environment and closed canopy, a tropical cloud forest produces lush vegetation and is one of the most biodiverse ecosystems on the earth. *(© G. Dimijian/Photo Researchers. Reproduced by permission.)*

native Americans, they were like walking biological warfare weapons.

Evaluating Ecosystems

The ease with which Europeans subdued Native Americans fueled the belief that Europeans were superior, but, as Diamond showed, if anything was superior, it was the ecosystems of the Old World. This "superiority" relates in large part to the diversity of organisms an ecosystem possesses. Many millions of years ago, Earth's oceans and lands were populated with just a few varieties of single-cell organisms, but over time increasing differentiation of species led to the development of the much more complex ecosystems we know now.

Such differentiation is essential, given the many basic types of ecosystem that the world has to offer: forests and grasslands, deserts and aquatic environments, mountains and jungles. Among the many ways that these ecosystems can be evaluated, aside from such obvious parameters as relative climate, is in terms of abundance and complexity of species.

Abundance and complexity. The biota (a combination of all flora and fauna, or plant and animal life, respectively) in a desert or the Arctic tundra is much less complex than that of a tropical rain forest or, indeed,

almost any kind of forest, because far fewer species can live in a desert or tundra environment. For this reason, it is said that a desert or tundra ecosystem is less complex than a forest one. There may be relatively large numbers of particular species in a less complex ecosystem, however, in which case the ecosystem is said to be abundant though not complex in a relative sense.

Another way to evaluate ecosystems is in terms of productivity. This concept refers to the amount of biomass—potentially burnable energy—produced by green plants as they capture sunlight and use its energy to create new organic compounds that can be consumed by local animal life. Once again, a forest, and particularly a rain forest, has a very high level of productivity, whereas a desert or tundra ecosystem does not.

FORESTS

Now let us look more closely at a full-fledged ecosystem—that of a forest—in action. It might seem that all forests are the same, but this could not be less the case. A forest is simply any ecosystem dominated by tree-sized woody plants. Beyond that, the characteristics of weather, climate, elevation, latitude, topography, tree species, varieties of animal species, moisture levels, and numerous other parameters create the potential for an almost endless diversity of forest types.

In fact, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) defines 24 different types of forest, which are divided into two main groups. On the one hand, there are those forests with a closed canopy at least 16.5 ft. (5 m) high. The canopy is the upper portion of the trees in the forest, and closed-canopy forests are so dense with vegetation that from the ground the sky is not visible. On the other hand, the UNESCO system encompasses open woodlands with a shorter, more sparse, and unclosed canopy. The first group tends to be tropical and subtropical (located at or near the equator), while the second typically is located in temperate and subpolar forests—that is, in a region between the two tropical latitudes and the Arctic and Antarctic circles, respectively. In the next paragraphs, we examine a few varieties of forest as classified by UNESCO.

TROPICAL AND SUBTROPICAL FORESTS. Tropical rain forests are complex ecosystems with a wide array of species. The dominant tree type is an angiosperm (a type of plant that produces flowers during sexual reproduction), known colloquially as tropical hardwoods. The climate and weather are what one would expect to find in a place called a tropical rain forest, that is, rainy and warm. When the rain falls, it cools things down, but when the sun comes back out, it turns the world of the tropical rain forest into a humid, sauna-like environment.

Naturally, the creatures that have evolved in and adapted to a tropical rain forest environment are those capable of enduring high humidity, but they are tolerant of neither extremely cool conditions nor drought. Within those parameters, however, exists one of the most biodiverse ecosystems on Earth: the tropical rain forest is home to an astonishing array of animals, plants, insects, and microorganisms. Indeed, without the tropical rain forest, terrestrial (land-based) animal life on Earth would be noticeably reduced.

In the tropics, by definition the four seasons to which we are accustomed in temperate zones—winter, spring, summer, and fall—do not exist. In their place there is a rainy season and a dry season, but there is no set point in the year at which trees shed their leaves. In a tropical and subtropical evergreen forest conditions are much drier than in the rain forest, and individual trees or tree species may shed their leaves as a result of dry conditions. All trees and species do not do so at the same time, however, so the canopy remains rich in foliage year-round—hence the term evergreen. As with a rain forest, the evergreen forest possesses a vast diversity of species.

In contrast to the two tropical forest ecosystems just described, a mangrove forest is poor in species. In terms of topography and landform, these forests are found in low-lying, muddy regions near saltwater. Thus, the climate is likely to be humid, as in a rain forest, but only organisms that can tolerate flooding and high salt levels are able to survive there. Mangrove trees, a variety of angiosperm, are suited to this environment and to the soil, which is poor in oxygen.

TEMPERATE AND SUBARCTIC FORESTS. Among the temperate and subarctic forest types are temperate deciduous forests, containing trees that shed their leaves seasonally, and temperate and subarctic evergreen conifer forests, in which the trees produce cones bearing seeds. These are forest types familiar to most people in the continental United

States. The first variety is dominated by such varieties as oak, walnut, and hickory, while the second is populated by pine, spruce, or fir as well as other types, such as hemlock.

Less familiar to most Americans outside the West Coast are temperate winter-rain evergreen broadleaf forests. These forests are dominated by evergreen angiosperms and appear in regions that have both a pronounced wet season and a summer drought season. Such forests can be found in southern California, where an evergreen oak of the *Quercus* genus is predominant. Even less familiar to Americans is the temperate and subpolar evergreen rain forest, which is found in the Southern Hemisphere. Occurring in a wet, frost-free ocean environment, these forests are dominated by such evergreen angiosperms as the southern beech and southern pine.

Angiosperms vs. Gymnosperms

Several times we have referred to angiosperms, a name that encompasses not just certain types of tree but also all plants that produce flowers during sexual reproduction. The name, which comes from Latin roots meaning "vessel seed," is a reference to the fact that the plant keeps its seeds in a vessel whose name emphasizes these plants' sexual-type reproduction: an ovary.

Angiosperms are a beautiful example of how a particular group of organisms can adapt to specific ecosystems and do so in a way much more efficient than did their evolutionary forebear. Flowering plants evolved only about 130 million years ago, by which time Earth had long since been dominated by another variety of seed-producing plant, the gymnosperm, of which pines and firs are an example. Yet in a relatively short period of time, from the standpoint of the earth sciences, angiosperms have gone on to become the dominant plants in the world. Today, about 80% of all living plant species are flowering plants.

ANGIOSPERM VS. GYMNOSPERM SEEDS. How did they do this? They did it by developing a means to coexist more favorably than gymnosperms with the insect and animal life in their ecosystems. Gymnosperms produce their seeds on the surface of leaflike structures, making the seeds vulnerable to physical damage and drying as the wind whips the branches back and forth. Furthermore, insects and other animals view gymnosperm seeds as a source of nutrition.

In an angiosperm, by contrast, the seeds are tucked away safely inside the ovary. Furthermore, the evolution of the flower not only has added a great deal of beauty to the world but also has provided a highly successful mechanism for sexual reproduction. This sexual reproduction makes it possible to develop new genetic variations, as genetic material from two individuals of differing ancestry come together to produce new offspring.

GYMNOSPERM POLLINATION. Gymnosperms reproduce sexually as well, but they do so by a less efficient method. In both cases, the trees have to overcome a significant challenge: the fact that sexual reproduction normally requires at least one of the individual plants to be mobile. Gymnosperms package the male reproductive component in tiny pollen grains, which are released into the wind. Eventually, the grains are blown toward the female component of another individual plant of the same species.

This method succeeds well enough to sustain large and varied populations of gymnosperms but at a terrific cost, as is evident to anyone who lives in a region with a high pollen count in the spring. A yellow dust forms on everything. So much pollen accumulates on window sills, cars, mailboxes, and roofs that only a good rain (or a car wash) can take it away, and one tends to wonder what good all this pollen is doing for the trees.

The truth is that pollination is wasteful and inefficient. Like all natural mechanisms, it benefit the overall ecosystem, in this case, by making nutrient-rich pollen grains available to the soil. Packed with energy, pollen grains contain large quantities of nitrogen, making them a major boost to the ecosystem if not to the human environment. But it costs the gymnosperm a great deal, in terms of chemical and biological energy and material, to produce pollen grains, and the benefits are much more uncertain.

Pollen *might* make it to the right female component, and, in fact, it will, given the huge amounts of pollen produced. Yet the overall system is rather like trying to solve an economic problem by throwing a pile of dollar bills into the air and hoping that some of the money lands in the right place. For this reason, it is no surprise

KEY TERMS

ABUNDANCE: A measure of the degree to which an ecosystem possesses large numbers of particular species. An abundant ecosystem may or may not have a wide array of different species. Compare with *complexity.*

ANGIOSPERM: A type of plant that produces flowers during sexual reproduction.

BIOGEOCHEMICAL CYCLES: The changes that particular elements undergo as they pass back and forth through the various earth systems and particularly between living and nonliving matter. The elements involved in biogeochemical cycles are hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur.

BIOTA: A combination of all flora and fauna (plant and animal life, respectively) in a region.

CANOPY: The upper portion of the trees in a forest. In a closed-canopy forest the canopy (which may be several hundred feet, or well over 50 meters, high) protects the soil and lower areas from sun and torrential rainfall.

CARNIVORE: A meat-eating organism.

COMPLEXITY: A measure of the degree to which an ecosystem possesses a wide array of species. These species may or may not appear in large numbers. Compare with *abundance.*

COMPOUND: A substance made up of atoms of more than one element chemically bonded to one another.

DECOMPOSERS: Organisms that obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. The principal forms of decomposer are bacteria and fungi.

DECOMPOSITION REACTION: A chemical reaction in which a compound is broken down into simpler compounds or into its constituent elements. On Earth, this often is achieved through the help of detritivores and decomposers.

DETRITIVORES: Organisms that feed on waste matter, breaking down organic material into inorganic substances that then can become available to the biosphere in the form of nutrients for plants. Their function is similar to that of decomposers, but unlike decomposers—which tend to be bacteria or fungi—detritivores are relatively complex organisms, such as earthworms or maggots.

that angiosperms gradually are overtaking gymnosperms.

ANGIOSPERM POLLINATION. The angiosperm overcomes its own lack of mobility by making use of mobile organisms. Whereas insects and animals pose a threat to gymnosperms, angiosperms actually put bees, butterflies, hummingbirds, and other flower-seeking creatures to work aiding their reproductive process. By evolving bright colors, scents, and nectar, the flowers of angiosperms attract animals, which travel from one flower to another, accidentally moving pollen as they do.

Because of this remarkably efficient system, animal-pollinated species of flowering plants do not need to produce as much pollen as gymnosperms. Instead, they can put their resources into other important functions, such as growth and greater seed production. In this way, the angiosperm solves its own problem of reproduc-

KEY TERMS CONTINUED

ECOSYSTEM: A community of interdependent organisms along with the inorganic components of their environment.

ELEMENT: A substance made up of only one kind of atom. Unlike compounds, elements cannot be broken chemically into other substances.

ENERGY TRANSFER: The flow of energy between organisms in a food web.

FOOD WEB: A term describing the interaction of plants, herbivores, carnivores, omnivores, decomposers, and detritivores in an ecosystem. Each consumes nutrients and passes it along to other organisms. Earth scientists typically prefer this name to *food chain,* an everyday term for a similar phenomenon. A food chain is a series of singular organisms in which each plant or animal depends on the organism that precedes or follows it. Food chains rarely exist in nature.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

GYMNOSPERM: A type of plant that reproduces sexually through the use of seeds that are exposed, not hidden in an ovary, as with an angiosperm.

HERBIVORE: A plant-eating organism.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

NICHE: A term referring to the role that a particular organism plays within its biological community.

OMNIVORE: An organism that eats both plants and other animals.

ORGANIC: At one time, chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon and hydrogen, thus excluding carbonates (which are minerals) and oxides, such as carbon dioxide.

PHOTOSYNTHESIS: The biological conversion of light energy (that is, electromagnetic energy) from the Sun to chemical energy in plants.

SYSTEM: Any set of interactions that can be set apart mentally from the rest of the universe for the purposes of study, observation, and measurement.

tion—and as a side benefit adds enormously to the world's beauty.

The Complexity of Ecosystems

The relationships between these two types of seed-producing plant and their environments illustrate, in a very basic way, the complex interactions between species in an ecosystem. Environmentalists often speak of a "delicate balance" in the natural world, and while there is some dispute as to how delicate that balance is—nature shows an amazing resilience in recovering from the worst kinds of damage—there is no question that a balance of some kind exists.

To put it another way, an ecosystem is an extraordinarily complex environment that brings together biological, geologic, hydrologic, and atmospheric components. Among these components are trees and other plants; animals, insects,

and microorganisms; rocks, soil, minerals, and landforms; water in the ground and on the surface, flowing or in a reservoir; wind, sun, rain, moisture; and all the other specifics that make up weather and climate.

In the present context, we have not attempted to provide anything even approaching a comprehensive portrait of an ecosystem, drawing together all or most of the aspects described in the preceding paragraph. A full account of even the simplest ecosystem would fill an entire book. Given that level of complexity, it is safe to say that one should be very cautious before tampering with the particulars of an ecosystem. The essay on Ecology and Ecological Stress concerns what happens when such tampering occurs.

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ECOLOGY AND ECOLOGICAL STRESS

CONCEPT

Ecology is the study of the relationships between organisms and their environments. As such, it is subsumed into the larger subject of ecosystems, which encompasses both living and nonliving components of the environment. As a study of the biological aspect of ecosystems, ecology is properly a part of the biological sciences rather than the earth sciences; however, in practice it is difficult to draw a line between the disciplines. This is especially the case inasmuch as the study of the environment involves such aspects as soil science, where earth sciences and ecology meet. This fact, combined with increasing concerns over ecological stresses, such as the increase of greenhouse gases in the atmosphere, warrants the consideration of ecology in an earth sciences framework.

HOW IT WORKS

Ecosystems, Biological Communities, and Ecology

An ecosystem is the complete community of living organisms and the nonliving materials of their surroundings. It therefore includes components that represent the atmosphere, the hydrosphere (all of Earth's waters, except for moisture in the atmosphere), the geosphere (the soil and extreme upper portion of the continental crust), and the biosphere. The biosphere includes all living things: plants (from algae and lichen to shrubs and trees); mammals, birds, reptiles, amphibians, aquatic life, and insects as well as all manner of microscopic forms, including bacteria and viruses. In addition, the biosphere draws together all formerly living things that have not yet decomposed.

The components of the biosphere are united not only by the fact that all of them are either living or recently living but also by the food web. The food web, discussed in much detail within the context of Ecosystems, is a complex network of feeding relationships and energy transfers between organisms. At various levels and stages of the food web are plants; herbivores, or plant-eating organisms; carnivores (meat-eating organisms); omnivores (organisms that eat both meat and plants); and, finally, decomposers and detritivores, which obtain their energy from the chemical breakdown of dead organisms.

ECOLOGY. When discussing the living components of an ecosystem—that is, those components drawn from the biosphere—the term biological community is used. This also may be called *biota,* which refers to all flora and fauna, or plant and animal life, respectively, in a particular region. The relationship between these living things and their larger environment, as we have noted, is called ecology. Pioneered by the German zoologist Ernst Haeckel (1834–1919), ecology was long held in disdain by the world scientific community, in part because it seemed to defy classification as a discipline. Though its roots clearly lie in biology, its broadly based, multidisciplinary approach seems more attuned to the earth sciences.

In any case, ecology long since has gained the respect it initially failed to receive, and much of that change has to do with a growing acceptance of two key concepts. On the one hand, there is the idea that all of life is interconnected and that the living world is tied to the nonliving, or

inorganic, world. This is certainly a prevailing belief in the modern-day earth sciences, with its systems approach (see Earth Systems). On the other hand, there is the gathering awareness that certain aspects of industrial civilization may have a negative impact on the environment.

Clearly, the ecosystem as a whole is held together by tight bonds of interaction, but where the biological community is concerned, those bonds are even tighter. For the biological community to survive and thrive, a balance must be maintained between consumption and production of resources. Nature provides for that balance in numerous ways, but beginning in the late twentieth century, environmentalists in the industrialized world became increasingly concerned over the possibly negative effects their own societies exert on Earth's ecosystems and ecological communities.

Climax and Succession

One of the concerns raised by environmentalists is the issue of endangered species, or varieties of animal whose existence is threatened by human activities. In fact, nature itself sometimes replaces biological communities in a process called succession. Succession involves the progressive replacement of earlier biological communities with others over time. Coupled with succession is the idea of climax, a theoretical notion intended to describe a biological community that has reached a stable point as a result of ongoing succession.

Succession typically begins with a disturbance exerted on the preexisting ecosystem, and this disturbance usually is followed by recovery. This recovery may constitute the full extent of the succession process, at which point the community is said to have reached its climax point. Whether or not this happens depends on such particulars as climate, the composition of the soil, and the local biota.

There are two varieties of succession, primary and secondary. Primary succession occurs in communities that have never experienced significant modification of biological processes. In other words, the community affected by primary succession is "virgin," and primary succession typically involves enormous stresses. On the other hand, secondary succession happens after disturbances of relatively low intensity, such that the regenerative capacity of the local biota has not been altered significantly. Secondary succession takes place in situations where the biological community has experienced alteration.

Niche

Whereas climax and succession apply to broad biological communities, the term niche refers to the role a particular organism or species plays within the larger community. Though the concept of niche is abstract, it is unquestionable that each organism plays a vital role and that the totality of the ecosystem would suffer stress if a large enough group of organisms were removed from it. Furthermore, given the apparent interrelatedness of all components in a biological community, every species must have a niche—even human beings.

An interesting idea related to the niche is the concept of an indicator species: a plant or animal that by its presence, abundance, or chemical composition demonstrates a particular aspect of the character or quality of the environment. Indicator species can, for instance, be plants that accumulate large concentrations of metals in their tissues, thus indicating a preponderance of metals in the soil. This metal could indicate valuable deposits nearby, or it could serve as a sign that the soil is being contaminated.

In the rest of this essay, we explore a few examples of ecological stress—situations in which the relationship between organisms and environment has been placed under duress. We do not attempt to explore the ideas of succession, climax, niche, or indicator species with any consistency or depth; rather, our purpose in briefly discussing these terms is to illustrate a few of the natural mechanisms observed or hypothesized by ecologists in studying natural systems. The vocabulary of ecology, in fact, is as complex and varied as that of any natural science, and much of it is devoted to the ways in which nature responds to ecological stress.

REAL-LIFE APPLICATIONS

Deforestation

In Ecosystems, we discuss a number of forest types, whose makeup is determined by climate and the dominant tree varieties. Here let us consider what happens to a forest—particularly an old-growth forest—that experiences significant



Rain forest destruction by fire in Madagascar. Such deforestation affects the carbon balance in the atmosphere and the diversity of species on Earth. *(© Daniel Heuclin/Photo Researchers. Reproduced by permission.)*

disturbance. Actually, the term deforestation can describe any interruption in the ordinary progression of the forest's life, including clear-cut harvesting, even if the forest fully recovers.

Deforestation can take place naturally, as a result of changes in the soil and climate, but the most significant cases of deforestation over the past few thousand years have been the result of human activities. Usually, deforestation is driven by the need to clear land or to harvest trees for fuel and, in some cases, building. Though deforestation has been a problem the world over, since the 1970s it has become more of an issue in developing countries.

DEVELOPED AND DEVELOPING NATIONS. In developed nations such as the United States, environmental activism has raised public awareness concerning deforestation and has led to curtailment of large-scale cutting in forests deemed important environmental habitats. By contrast, developing nations, such as Brazil, are cutting down their forests at an alarming rate. Generally, economics is the driving factor, with the need for new agricultural land or the desire to obtain wood and other materials driving the deforestation process.

Yet the deforestation of such valuable reserves as the Amazon rain forest is an environmental disaster in the making: as noted in Soil Conservation, the soil in rain forests is typically "old" and leached of nutrients. Without the constant reintroduction of organic material from the



Old-growth forests are home to the northern spotted owl, recognized as an endangered species because of the destruction of its habitat. *(© T. Davis/Photo Researchers. Reproduced by permission.)*

plants and animals of the rain forests, it would be too poor to grow anything. Therefore, when nations cut down their own rain forest lands, in effect, they are killing the golden goose to get the egg. Once the rain forest is gone, the land itself is worthless.

Consequences of deforestation. Deforestation has several extremely serious consequences. From a biological standpoint, it greatly reduces biodiversity, or the range of species in the biota. In the case of tropical rain forests as well as old-growth forests, certain species cannot survive once the environmental structure has been ruptured. From an environmental perspective, it leads to dangerous changes in the carbon content of the atmosphere, discussed later in this essay. In the case of old-growth forests or rain forests, deforestation removes an irreplaceable environmental asset that contributes to the planet's biodiversity—and to its oxygen supply.

Even from a human standpoint, deforestation takes an enormous toll. Economically, it depletes valuable forest resources. Furthermore, deforestation in many developing countries often is accompanied by the displacement of indigenous peoples. Other political and social horrors sometimes lurk in the shadows: for example, Brazil's forests are home to charcoal plants that amount to virtual slave-labor camps. Indians are lured from cities with promises of high income and benefits, only to arrive and find that the situation is quite different from what was advertised. Having paid the potential employer for transportation to the work site, however, they are unable to afford a return ticket and must labor to repay the cost.

Old-Growth Forests

Old-growth forests represent a climax ecosystem—one that has come to the end of its stages of succession. They are dominated by trees of advanced age (hence the name *old-growth*), and the physical structure of these ecosystems is extraordinarily complex. In some places the canopy, or "rooftop," of the forest is dense and layered, while in others it has gaps. Tree sizes vary enormously, and the forest is littered with the remains of dead trees.

An old-growth forest, by definition, takes a long time to develop. Not only must it have been free from human disturbance, but it also must have been spared various natural types of disturbance that bring about succession: catastrophic storms or wildfire, for instance. For this reason, most old-growth forests are rain forests in tropical and temperate environments. Among North American old-growth forests are those of the United States Pacific Northwest as well as those in adjoining regions of southwestern Canada.

The spotted owl. These old-growth forests are home to a bird that, in the 1980s and 1990s, became well known both to environmentalists and to their critics: the northern spotted owl, or *Strix occidentalis caurina.* A nonmigratory bird, the spotted owl has a breeding pattern such that it requires large tracts of old-growth, moist-to-wet conifer forest—that is, a forest dominated by cone-producing trees—as its habitat. Given the potential economic value of old-growth forests in the region, the situation became one of heated controversy.

On the one hand, environmentalists insisted that the spotted owl's existence would be threatened by logging, and, on the other hand, representatives of the logging industry and the local

community maintained that prevention of logging in the old-growth forests would cost jobs and livelihoods. The question was not an easy one, pitting the interests of the environment against those of ordinary human beings. By the early 1990s, the federal government had stepped in on the side of the environmentalists, having recognized the spotted owl as a threatened species under the terms of the U.S. Endangered Species Act of 1973. Nonetheless, controversy over the spotted owl—and over the proper role of environmental, economic, and political concerns in such situations—continues.

THE GREENHOUSE EFFECT

Deforestation and other activities pose potential dangers to our atmosphere. In particular, such activities have led to an increasing release of greenhouse gases, which may cause the warming of the planet. As discussed in Energy and Earth, the greenhouse effect, in fact, is a natural process. Though it is typically associated, in the popular vocabulary at least, with the destructive impact of industrial civilization on the environment, it is an extremely effective mechanism whereby Earth makes use of energy from the Sun.

Rather than simply re-radiating solar radiation, Earth traps some of this heat in the atmosphere with the help of greenhouse gases, such as carbon dioxide. As in the case of most natural processes, however, if a little bit of carbon dioxide in the atmosphere is good, this does not mean that a lot is better.

As noted in the essay Carbon Cycle, all living things contain carbon in certain characteristic structures; hence, the term *organic* refers to this type of carbon content. Though carbon dioxide is not an organic compound, it is emitted by animals: they breathe in oxygen, which undergoes a chemical reaction in their carbon-based bodies, and, as a result, carbon dioxide is released. Plants, on the other hand, receive this carbon dioxide and, through a chemical process in their own cellular structures, take in the carbon while releasing the oxygen.

THE RESULT OF CUTTING MATURE FORESTS. Mature forests, such as those of the old-growth variety, contain vast amounts of carbon in the form of living and dead organic material: plants, animals, and material in the soil. Because this quantity is much greater than in a younger forest, when deforestation occurs in a mature forest ecosystem, the mature forest will be replaced by an ecosystem that contains much smaller amounts of carbon.

Ultimately, the carbon from the former ecosystem will be released to the atmosphere in the form of carbon dioxide. This will happen quickly, if the biomass of the forest is burned, or more slowly, if the timber from the forest is used for a long periods of time, for instance, in the building of houses or other structures.

Before humans began cutting down forests, Earth's combined vegetation stored some 990 billion tons (900 billion metric tons) of carbon, 90% of it appeared in forests. Today only about 616 billion tons (560 billion metric tons) of carbon are stored in Earth's vegetation, and the amount is growing smaller as time passes. At the same time, the amount of carbon dioxide in the atmosphere has increased from about 270 parts per million (ppm) in 1850 to about 360 ppm in 2000, and, again, the increase continues.

SHOULD WE BE WORRIED? Given this rise in atmospheric carbon dioxide as a result of deforestation—not to mention the more well-known cause, burning of fossil fuels—it is no wonder that atmospheric scientists and environmentalists are alarmed. Some of these scientists hypothesize that larger concentrations of carbon dioxide in the atmosphere will lead to increased intensity of the greenhouse effect. If this is true, it is possible that global warming will ensue, an eventuality that could have enormous implications for human survival. As a worst-case scenario, the polar ice cap (see Glaciology) could melt, submerging the cities of Earth.

Before succumbing to the sort of doomsday thinking and scaremongering for which many environmentalists are criticized, however, it is important to recognize that several contingencies are involved: *if* carbon dioxide in the atmosphere causes an increase in the intensity of the greenhouse effect, it *could* cause global warming. The fact is that despite a few mild winters at the end of the twentieth century, it is far from clear that the planet is warming. The winter of 1993, for instance, produced one of the worst blizzards that the eastern United States has ever seen.

As recently as the mid-1970s some environmentalists claimed that Earth actually is *cooling*—a response to a spate of cold winters in that period. The fact of the matter is that climate cycles are difficult to determine and require the

KEY TERMS

BIOACCUMULATION: The buildup of toxic chemical pollutants in the tissues of individual organisms.

BIOLOGICAL COMMUNITY: The living components of an ecosystem.

BIOMAGNIFICATION: The increase in bioaccumulated contamination at higher levels of the food web. Biomagnification results from the fact that larger organisms consume larger quantities of food—and, hence, in the case of polluted materials, more toxins.

BIOSPHERE: A combination of all living things on Earth—plants, mammals, birds, reptiles, amphibians, aquatic life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

BIOTA: A combination of all flora and fauna (plant and animal life, respectively) in a region.

CANOPY: The upper portion of the trees in a forest. In a closed-canopy forest, the canopy (which may be several hundred feet, or well over 50 meters, high) protects the soil and lower areas from sun and torrential rainfall.

CARNIVORE: A meat-eating organism.

CLIMAX: A theoretical notion intended to describe a biological community that has reached a stable point as a result of ongoing succession.

DECOMPOSERS: Organisms that obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. The principal forms of decomposer are bacteria and fungi.

DECOMPOSITION REACTION: A chemical reaction in which a compound is broken down into simpler compounds or into its constituent elements. On Earth, this often is achieved through the help of detritivores and decomposers.

DETRITIVORES: Organisms that feed on waste matter, breaking organic material down into inorganic substances that then can become available to the biosphere in the form of nutrients for plants. Their function is similar to that of decomposers; however, unlike decomposers—which tend to be bacteria or fungi—detritivores are relatively complex organisms, such as earthworms or maggots.

ECOLOGY: The study of the relationships between organisms and their environments.

perspective of several centuries' worth of data (at least), rather than just a few years' worth. (See Glaciology for a discussion of the Little Ice Age, which took place just a few centuries ago.)

Nonetheless, it is important to be aware of the legitimate environmental concerns raised by the increased presence of carbon dioxide in the atmosphere due to human activities. Atmospheric scientists continue to monitor levels of greenhouse gases and to form hypotheses regarding the ultimate effect of such activities as deforestation and the burning of fossil fuels.

Bioaccumulation and Biomagnification

As we have seen in a number of ways, one of the key concepts of ecological studies is also a core principle in the modern approach to the earth sciences. In both cases, there is the idea that a disturbance in one area can lead to serious conse-

KEY TERMS CONTINUED

ECOSYSTEM: A community of interdependent organisms along with the inorganic components of their environment.

ENERGY TRANSFER: The flow of energy between organisms in a food web.

FOOD WEB: A term describing the interaction of plants, herbivores, carnivores, omnivores, decomposers, and detritivores in an ecosystem. Each of these organisms consumes nutrients and passes them along to other organisms. Earth scientists typically prefer this name to food chain, an everyday term for a similar phenomenon. A food chain is a series of singular organisms in which each plant or animal depends on the organism that precedes or follows it. Food chains rarely exist in nature.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

GREENHOUSE EFFECT: Warming of the lower atmosphere and surface of Earth. This occurs because of the absorption of long-wavelength radiation from the planet's surface by certain radiatively active gases, such as carbon dioxide and water vapor, in the atmosphere. These gases are heated and ultimately re-radiate energy to space at an even longer wavelength.

HERBIVORE: A plant-eating organism.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere, but including all oceans, lakes, streams, groundwater, snow, and ice.

NICHE: A term referring to the role that a particular organism plays within its biological community.

OMNIVORE: An organism that eats both plants and other animals.

ORGANIC: At one time chemists used the term organic only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals) and oxides, such as carbon dioxide.

SUCCESSION: The progressive replacement of earlier biological communities with others over time.

SYSTEM: Any set of interactions that can be set apart from the rest of the universe for the purposes of study, observation, and measurement.

quences elsewhere. The interconnectedness of components in the environment thus makes it impossible for any event or phenomenon to be truly isolated.

A good example of this is biomagnification. Biomagnification is the result of bioaccumulation, or the buildup of toxic chemical pollutants in the tissues of individual organisms. Part of what makes these toxins dangerous is the fact that the organism cannot process them easily either by metabolizing them (i.e., incorporating them into the metabolic system, as one does food or water) or by excreting them. Yet the organism ultimately does release some toxins—by passing them on to other members of the food web. This increase in contamination at higher levels of the food web is known as biomagnification.

THE PROCESS OF BIOMAGNIFICATION. Among the most prominent examples of chemical pollutants that are bioac-

cumulated are such pesticides as DDT (dichlorodiphenyl-trichloroethane). DDT is a chlorinated hydrocarbon (see Economic Geology) used as an insecticide. Because of its hydrocarbon base, DDT is highly soluble in oils—and in the fat of organisms. Once pesticides such as DDT have been sprayed, rain can wash them into creeks and, finally, lakes and other bodies of water, where they are absorbed by creatures that drink or swim in the water.

Atmospheric deposition, for instance, from industrial smokestacks or automobile emissions, is another source of toxins. Sludge from a sewage treatment plant can make its way into water sources, spreading all sorts of pollutants to the food web. Whatever the case, these toxins usually enter the food web by attaching to the smallest components. Particles of pollutant may stick to algae, which are so small that the toxin does little damage at this level of the food web. But even a small herbivore, such as a zooplankton, when it consumes the algae, takes in larger quantities of the pollutant, and thus begins the cycle of biomagnification.

By the time the toxin has passed from a zooplankton to a small fish, the amount of pollutant in a single organism might be 100 times what it was at the level of the algae. The reason, again, is that the fish can consume 10 zooplankton that each has consumed 10 algae. (These particular numbers, of course, are used simply for the sake of convenience.) By the time the toxins have passed on to a few more levels in the food web, they might be appearing in concentrations as great as 10,000 times their original amount.

DDT BIOMAGNIFICATION. For a period of about two decades before 1972, DDT was used widely in the United States to help control the populations of mosquitoes and other insects. Eventually, however, it found its way into water sources and fish species through the process we have described. Predatory birds, such as osprey, peregrine falcons, and brown pelicans, consumed these fish. So, too, did the bald eagle, which has long been a protected species owing to its role as America's national symbol.

DDT levels became so high that the birds' eggshells became abnormally thin, and adult birds sitting on nests accidentially would break the shells of unhatched eggs. As a result, baby birds died, and populations of these species also died. Public awareness of this phenomenon, raised by environmentalists in the late 1960s and early 1970s, led to the banning of DDT spraying in 1972. Since that time, populations of many predatory birds have increased dramatically.

ADDRESSING ECOLOGICAL CONCERNS. In the case of DDT biomagnification, humans were not directly involved, because the species of birds affected were not ones that people consume for food. Yet bioaccumulation and biomagnification have threatened humans. For example, in the 1950s, cows fed on grass that had been exposed to nuclear radiation and this radioactive material found its way into milk. Another example occurred during the 1970s and 1980s, when fish, such as tuna, were found to contain abnormally high levels of mercury.

This led the federal government and some states to issue warnings against the consumption of certain types of fish, owing to bioaccumulated levels of toxic pollutants. Obviously, such measures, however well intentioned, are just cosmetic fixes for larger problems. In the long run, what is needed is a systemic ecological approach that attempts to address problems such as biomagnification and the accumulation of greenhouse gases by approaching the root causes.

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WATER AND THE EARTH

HYDROLOGY

THE HYDROLOGIC CYCLE

GLACIOLOGY

HYDROLOGY

CONCEPT

Hydrology is among the principal disciplines within the larger framework of hydrologic sciences, itself a subcategory of earth sciences study. Of particular importance to hydrology is the hydrologic cycle by which water is circulated through various earth systems above and below ground. But the hydrologic cycle is only one example of the role water plays in the operation of earth systems. Outside its effect on living things, a central aspect of the hydrologic cycle, water is important for its physical and chemical properties. Its physical influence, exerted through such phenomena as currents and floods, can be astounding but no less amazing than its chemical properties, demonstrated in the fascinating realm of karst topography.

HOW IT WORKS

The Systems Approach

The modern study of earth sciences looks at the planet as a large, complex network of physical, chemical, and biological interactions. This is known as a systems approach to the study of Earth. The systems approach treats Earth as a combination of several subsystems, each of which can be viewed individually or in concert with the others. These subsystems are the geosphere, atmosphere, hydrosphere, and biosphere.

The geosphere is that part of the solid earth on which people live and from which are extracted the materials that make up our world: minerals and rocks as well as the organic products of the soil. In the latter area, the geosphere overlaps with the biosphere, the province of all living and recently living things; in fact, once a formerly living organism has decomposed and become part of the soil, it is no longer part of the biosphere and has become a component of the geosphere.

Overlap occurs between all spheres in one way or another. Thus, the hydrosphere includes all of the planet's waters, except for water that has entered the atmosphere in the form of evaporation. From the time moisture is introduced to the blanket of gases that surrounds the planet until it returns to the solid earth in the form of precipitation, water is a part of the atmosphere. This aspect of the planet's water is treated in the essay on Evapotranspiration and Precipitation.

THE HYDROSPHERE AND THE HYDROLOGIC CYCLE. All aspects of water on Earth, other than evaporation and precipitation, fall within the hydrosphere. This includes saltwater and freshwater, water on Earth's surface and below it, and all imaginable bodies of water, from mountain streams to underground waterways and from creeks to oceans. One of the fascinating things about water is that because it moves within the closed system of Earth, all the planet's water circulates endlessly. Thus, there is a chance that the water in which you take your next bath or shower also bathed Cleopatra or provided a drink to Charlemagne's horse.

On a less charming note, there is also a good chance that the water with which you brush your teeth once passed through a sewer system. Lest anyone panic, however, this has always been the case and always will be; as we have noted, water circulates endlessly, and one particular molecule may serve a million different functions.

Furthermore, as long as water continues to circulate through the various earth systems—that is, as long as it is not left to stagnate in a

pond—it undergoes a natural cleansing process. Modern municipal and private water systems provide further treatment to ensure that the water that people use for washing is at least reasonably clean. In any case, it is clear that the movement of water through the hydrologic cycle is a subject complex enough to warrant study on its own (see Hydrologic Cycle).

The Hydrologic Sciences

As noted in Studying Earth, the earth sciences can be divided into three broad areas: the geologic, hydrologic, and atmospheric sciences. Each of these areas corresponds to one of the "spheres," or subsystems within the larger earth system, that we have discussed briefly: geosphere, hydrosphere, and atmosphere.

The hydrologic sciences are concerned with the hydrosphere and its principal component, water. These disciplines include glaciology—the study of ice in general and glaciers in particular—and oceanography. Glaciology is discussed in a separate essay, and oceanography is examined briefly in the present context. Aside from these two areas of study, the central component of the hydrologic sciences is hydrology—its most basic discipline, as geology is to the geologic sciences.

OCEANOGRAPHY. Oceanography is the study of the world's saltwater bodies—that is, its oceans and seas—from the standpoint of their physical, chemical, biological, and geologic properties. These four aspects of oceanographic study are reflected in the four basic subdisciplines into which oceanography is divided: physical oceanography, chemical oceanography, marine geology, and marine ecology. Each represents the application of a particular science to the study of the oceans.

Physical oceanography, as its name implies, involves the study of physics as applied to the world's saltwater bodies. In general, it concerns the physical properties of the oceans and seas, including currents and tides, waves, and the physical specifics of seawater itself—that is, its temperature, pressure at particular depths, density in specific areas, and so on.

Just as physical oceanography weds physics to the study of seawater, chemical oceanography is concerned with the properties of the ocean as viewed from the standpoint of chemistry. These properties include such specifics as the chemical composition of seawater as well as the role the ocean plays in the biogeochemical cycles whereby certain chemical elements circulate between the organic and inorganic realms (see Biogeochemical Cycles, Carbon Cycle, and Nitrogen Cycle).

The biogeochemical focus of chemical oceanography implies an overlap with geochemistry. Likewise, marine geology exists at the nexus of oceanography and geology, involving, as it does, such subjects as seafloor spreading (see Plate Tectonics), ocean topography, and the formation of ocean basins. Finally, there is the realm where oceanography overlaps with biology, a realm known as marine ecology or biological oceanography. This subdiscipline is concerned with the wide array of life-forms, both plant and animal, that live in the oceans as well as the food webs whereby they interact with one another.

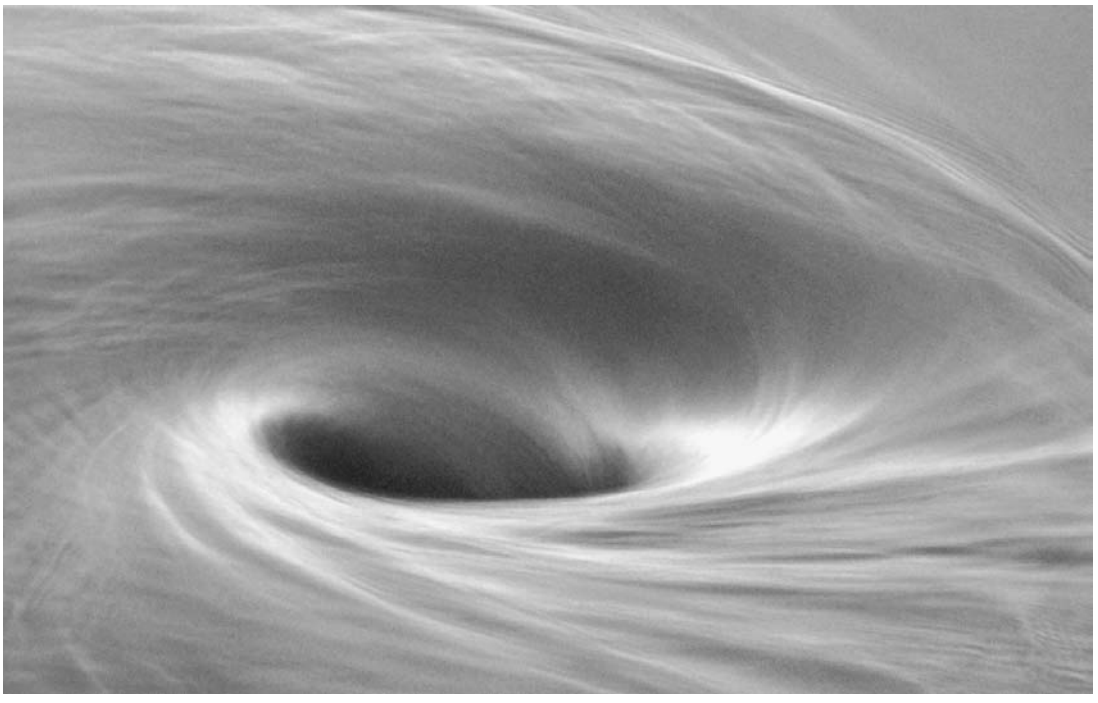
Introduction to Hydrology

As noted earlier, hydrology is the central field of the hydrologic sciences, dealing with the most basic aspects of Earth's waters. Among the areas of focus in hydrology are the distribution of water on the planet, its circulation through the hydrologic cycle, the physical and chemical properties of water, and the interaction between the hydrosphere and other earth systems.

Among the subdisciplines of hydrology are these:

- Groundwater hydrology: The study of water resources below ground.
- Hydrography: The study and mapping of large surface bodies of water, including oceans and lakes.
- Hydrometeorology: The study of water in the lower atmosphere, an area of overlap between the hydrologic and atmospheric sciences
- Hydrometry: The study of surface water—in particular, the measurement of its flow and volume.

THE WORK OF HYDROLOGISTS. Bringing together aspects of geology, chemistry, and soil science, hydrology is of enormous practical importance. Local governments, for instance, require hydrologic studies before the commencement of any significant building project, and hydrology is applied to such areas as the designation and management of flood plains. Hydrologists also are employed in the management of water resources, wastewater systems, and irrigation projects. The public use of water for



Whirlpools are created where two currents meet. Water tends to rotate in circles, clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. *(© B. Tharp/Photo Researchers. Reproduced by permission.)*

recreation and power generation also calls upon the work of hydrologists, who assist governments and private companies in controlling and managing water supplies.

Hydrologists in the field use a variety of techniques, some of them simple and time-honored and others involving the most cutting-edge modern technology. They may make use of highly sophisticated computer models and satellite remote-sensing technology, or they may apply relatively uncomplicated methods for the measurement of snow depth or the flow of rivers and streams. Local hydrologists searching for water may even avail themselves of the services of quasi-mystics who employ a nonscientific practice called *dowsing*. The latter method, which involves the sensing of underground water with a "magic" divining rod, sometimes is used, with varying degrees of success, to find water in rural areas.

REAL-LIFE APPLICATIONS

Currents

Ocean waters are continually moving, not only as waves hitting the shore (a function of the Moon's gravitational pull—see Sun, Moon, and Earth) but also in the form of currents. These are patterns of oceanic flow, many of them regular and unchanging and others susceptible to change as a result of shifts in atmospheric patterns and other parameters. Among the factors that affect the flow of currents are landmasses, wind patterns, and the Coriolis effect, or the deflection of water caused by the turning of Earth.

Landmasses on either side of the Atlantic, Pacific, and Indian Oceans act as barriers to the paths of currents. For instance, if Africa were not placed as it is, between the Atlantic and Indian Oceans, water in the equatorial region would flow uniformly from east to west, or from the Indian Ocean to the Atlantic. Likewise, the movement would be uniformly west to east at the poles, as it would be at the equator.

Such is the case just off the shores of Antarctica, where the Antarctic Circumpolar Current, without the obstruction of land barriers, consistently circles the globe in a west-to-east direction. On the other hand, at the southern extremity of Africa, far from the equator, the movement of water also would be uniform, but in this case from west to east. Because of these landmasses,

however, the movement of currents is much more complex.

Wind patterns also drive currents. These patterns work in tandem with the Coriolis effect, a term that generally describes a phenomenon that occurs with all particles on a rotating sphere such as Earth. The result of the Coriolis effect is that water tends to rotate in circles, clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere. (At the equator and poles, by contrast, the Coriolis effect is nonexistent.) Combined with prevailing winds, the Coriolis effect creates vast elliptical (oval-shaped) circulating currents called gyres.

Surface currents and their effect on climate. Among the basic types of currents are surface, tidal, and deep-water currents. In addition, a fourth type of current, a turbidity current, is of interest to oceanographers, hydrologists, and underwater geologists. Surface currents such as the Gulf Stream are the most well known variety, being the major form of current by which water circulates on the ocean's surface. Caused by the friction of atmospheric patterns—another type of current—moving over the sea, these currents largely are driven by winds. (Winds, in turn, are caused by differences in temperature between packets of air at differing altitudes—see Convection.)

Running as deep as 656 ft. (200 m), surface currents can be a powerful force. As a result of the Gulf Stream, for instance, a craft that sets sail eastward from the Caribbean is likely to be pulled quickly toward England. Of even greater importance is the impact of the Gulf Stream on climate. By moving warm waters in a northeasterly direction, it causes the European climate to be much warmer than it would be normally.

For instance, Boston, Massachusetts, and Rome, Italy, are on the same latitude, but whereas Boston is known for its icy winters, the mention of Rome rightly conjures images of sunshine and warmth. Likewise, London lies north of the 50th parallel, far above any city in the continental United States—including such places as International Falls, Minnesota, and Buffalo, New York, which are noted for their cruel winters. On the other hand, London, while it is far from balmy in wintertime, is many degrees warmer, thanks to the Gulf Stream.

Other types of current. Among the other types of currents are tidal currents, which are horizontal movements of water associated with the changing tides of the ocean. Their effect is felt primarily in the area between the continental shelf and the shore, where tidal-current phenomena such as riptides can pose a serious danger to swimmers. Deep-water currents, while they are less noticeable to people, are responsible for 90% of the water circulation that takes place in the ocean. Caused by variations in water density, which is a function of salt content (salinity) and temperature, these are slow-moving currents that move colder, denser water toward the depths of the ocean.

Then there are turbidity currents, which result from the mixing of relatively light water with water that has been made heavy by its sediment content. Earthquakes may cause these currents, which are local, fast movements of water along the ocean floor. Another cause of turbidity currents is the piling of sediment on underwater slopes. Turbidity currents play a major role in shaping the terrain of the ocean floor.

Flooding

Whereas currents arise in areas of Earth where water is "supposed" to be, floods, by definition, do not. They often occur in valleys or on coastlines and can be caused by various natural and man-made factors. Among natural causes are rains and the melting of snow and ice, while human-related causes can include poor engineering of irrigation or other water-management systems as well as the bursting of dams. In addition, the building of settlements too close to rivers and other bodies of water that are prone to flooding has resulted in the increase of human casualties from flooding over the centuries.

In terms of natural causes, changes in weather patterns typically are involved—but not always. For example, a low-lying coastal area may be susceptible to flooding at times when the ocean reaches high tide. (On the other hand, such weather conditions as low barometric pressure and high winds also can bring about heightened high tides.) Additionally, floods can be caused by earthquakes and other geologic phenomena that have no relation to the weather.

From ancient times people have located settlements near water. This settlement pattern resulted from the obvious benefits that accrued



THE FLOODWATERS OF THE MISSISSIPPI RISE TO 4 FT. (1.2 M), SURROUNDING THE PUMPING STATION IN HANNIBAL, MISSOURI. APART FROM NATURAL CAUSES, FLOODS CAN RESULT FROM INCONSISTENT FLOOD MANAGEMENT, POOR CIVIL ENGINEERING DESIGN, AND UNWISE AGRICULTURAL PRACTICES. *(AP/Wide World Photos. Reproduced by permission.)*

from access to water, and even though flooding was naturally a hazard, in some cases flooding itself was found to be beneficial. For the ancient Egyptians, the yearly cycles of flooding on the part of the Nile caused the deposition of rich soil, which played a major part in the fertility of the farmlands that, in turn, made possible the brilliant civilization of the pharaohs.

Along with these benefits, however, ancient peoples learned to fear the changes in weather and other circumstances that could bring about sudden flooding. This feeling is reflected, for instance, in Jesus' parable about the wise and foolish house builders. In the parable, a favorite Sunday school topic, the foolish man builds his house upon the sand, so that when the floods come, they sweep away his household. On the other hand, the wise man builds his house on rock, so that his household withstands the inevitable flood—an illustration about spiritual values that likewise reflects a reality of daily life in the ancient Near East.

HUMAN CAUSES AND EFFECTS. Humans can cause floods by such disastrous practices as clear-cutting of land and runaway grazing. Such activities remove vegetation, which holds soil in place and, in turn, keeps rivers and other bodies of water from flowing over onto the land. In addition, without vegetation to absorb rain, ground becomes saturated and thus susceptible to flooding. Not surprisingly, these unwise agricultural practices have helped bring about other disasters, such as the massive erosion of soil in the United States plains states that culminated in the dust bowl of the mid-1930s (see Soil Conservation).

Less well known than the dust bowl but still massive in its impact was the 1927 flood of the Mississippi River, which left more than a million people homeless. It, too, was in part the result of unwise practices, in this case, inconsistent flood management and civil engineering design, according to John M. Barry, the author of *Rising Tide: The Great Mississippi Flood of 1927 and How It Changed America.* As Barry indicated in his subtitle, the flood's impact went far beyond its direct effect on human lives or the landscape.

As Barry discusses in the book, the flood was a major cause behind the rise of the poor-white discontent in Louisiana that led to the governorship (and, in the opinion of some people, the dictatorship) of the notorious Huey P. Long (1893–1935). Long, who won election on promises to ease the suffering of the underclass, ulti-

mately became the virtual ruler of his state, with a degree of power that in the opinions of some pundits rivaled that of President Franklin D. Roosevelt—if not that of his other contemporaries, Adolf Hitler and Benito Mussolini. Of even greater long-term significance, Barry maintained, the flood brought about the large-scale flight of African Americans to the north and the shift of black political allegiance from the Republican Party to the Democratic Party.

Few people alive today remember the 1927 flooding, but plenty recall the devastating floods of 1993, which killed 52 people and left over 70,000 homeless. Human mismanagement could not be blamed for the flooding itself, an outgrowth of exceptionally high soil moisture levels remaining from the fall of 1992, as well as heavy precipitation that continued in early 1993. However, once again, human attempts to control the flooding were less than successful: of some 1,300 levees or embankments that had been built (partly as a result of the 1927 flood) to keep flood waters back, all but about 200 failed. The floods, which lasted from late June to mid-August, destroyed nearly 50,000 homes and rendered over 12,000 sq mi. (31,000 sq km) of farmland useless. The overall damage estimate was in the range of $15 to $20 billion.

POWER AND PREVENTION. It is no wonder that a flood can have such a far-reaching impact, given the enormous power of water running wild in nature. Water is extremely heavy: just a bathtub full of water can weigh as much 750 lb. (340 kg). And it can travel as fast as 20 MPH (32 km/h), giving it tremendous physical force. Under certain conditions, a flood just 1 in. (2.54 cm) in depth can have as much potential energy as 60,000 tons (54,400 metric tons) of TNT. A U.S. study of persons killed in natural disasters during the 20-year period that ended in 1967 found that of 443,000 victims, nearly 40%, or about 173,000, were killed in floods. The other 60% was made up of people killed in 18 different types of other natural disaster, including hurricanes, earthquakes, and tornadoes.

Given this great destructive potential, communities—often with the help of hydrologists—have devised several means to control floods. Among such methods are the construction of dams and the diversion of floodwaters away from populated areas to flood-control reservoirs. These reservoirs then release the water at a slower rate than it would be released in the situation of a flood, thus giving the soil time to absorb the excess water. About one-third of all reservoirs in the United States are used for this purpose.

Hydrologists are particularly important in helping communities protect against flooding by methods known as hazard zoning and minimizing encroachment. By studying historical records, along with geologic maps and aerial photographs, hydrologists and other planners can make recommendations regarding the zoning laws for a particular area, so that builders will take special precautions. In addition, they can help minimize encroachment—that is, ensure that new buildings are not located in such a way that they restrict the flow of water or cause water to pool up excessively.

Karst Topography

In contrast to the dramatic action of flooding or currents, karst topography is a more subtle but no less intriguing aspect of the ways in which water affects the dynamics of Earth. In this case, however, the effect is chemical rather than physical in origin. Karst topography is a particular variety of landscape created where water comes into contact with extremely soluble (easily dissolved in water) varieties of bedrock.

Karst is the German name for Kras, a region of Slovenia noted for its unusual landscape of strangely shaped white rock. In addition to the odd, funhouse forms of nightmarishly steep hills and twisting caves, much of it like something from a Dr. Seuss book, karst topography is noted for its absence of surface water, topsoil, or vegetation. The reason is that the bedrock comprises extremely soluble calcium carbonate minerals, such as limestone, gypsum, or dolomite.

Karst regions form as a result of chemical reactions between groundwater and bedrock. In the atmosphere and on the surface of the solid earth, water combines with carbon dioxide in the air, and this combination acts as a corrosive on calcium carbonate rocks. This corrosive or acidic material seeps into all crevices of the rock, developing into sinkholes and widening fissures over time. Gradually, it carves out enormous underground drainage systems and caves.

Sometimes the underground drainage structure collapses, leaving behind more odd shapes in the form of natural bridges and sink-

KEY TERMS

BIOGEOCHEMICAL CYCLES: The changes that particular elements undergo as they pass back and forth through the various earth systems and particularly between living and nonliving matter. The elements involved in biogeochemical cycles are hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur.

BIOSPHERE: A combination of all living things on Earth—plants, mammals, birds, reptiles, amphibians, aquatic life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

CORIOLIS EFFECT: The deflection of water caused by the rotation of Earth. The Coriolis effect causes water currents to move in circles—clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere.

GEOCHEMISTRY: A branch of the earth sciences, combining aspects of geology and chemistry, that is concerned with the chemical properties and processes of Earth—in particular, the abundance and interaction of chemical elements and their isotopes.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

HYDROLOGIC CYCLE: The continuous circulation of water throughout Earth and between various Earth systems.

HYDROLOGIC SCIENCES: Areas of the earth sciences concerned with the study of the hydrosphere. Among these disciplines are hydrology, glaciology, and oceanography.

HYDROLOGY: The study of the hydrosphere, including the distribution of water on Earth, its circulation through the hydrologic cycle, the physical and chemical properties of water, and the interaction between the hydrosphere and other earth systems.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

ORGANIC: At one time, chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals) and oxides, such as carbon dioxide.

SYSTEM: Any set of interactions that can be set apart mentally from the rest of the universe for the purposes of study, observation, and measurement.

holes. This is a variety of karst topography known as doline karst. Another type is cone or tower karst, which produces tall, jagged limestone peaks, such as the sharp hills that characterize the river landscape in many parts of China. The United States is home to the world's largest karst region, which includes the Mammoth cave system in Kentucky.

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THE HYDROLOGIC CYCLE

CONCEPT

The hydrologic cycle is the continuous circulation of water throughout Earth and between Earth's systems. At various stages, water—which in most cases is synonymous with the hydrosphere—moves through the atmosphere, the biosphere, and the geosphere, in each case performing functions essential to the survival of the planet and its life-forms. Thus, over time, water evaporates from the oceans; then falls as precipitation; is absorbed by the land; and, after some period of time, makes its way back to the oceans to begin the cycle again. The total amount of water on Earth has not changed in many billions of years, though the distribution of water does. The water that we see, though vital to humans and other living things, makes up only about 0.0001% of the total volume of water on Earth; far more is underground and in other compartments of the environment.

HOW IT WORKS

Water and the Hydrosphere

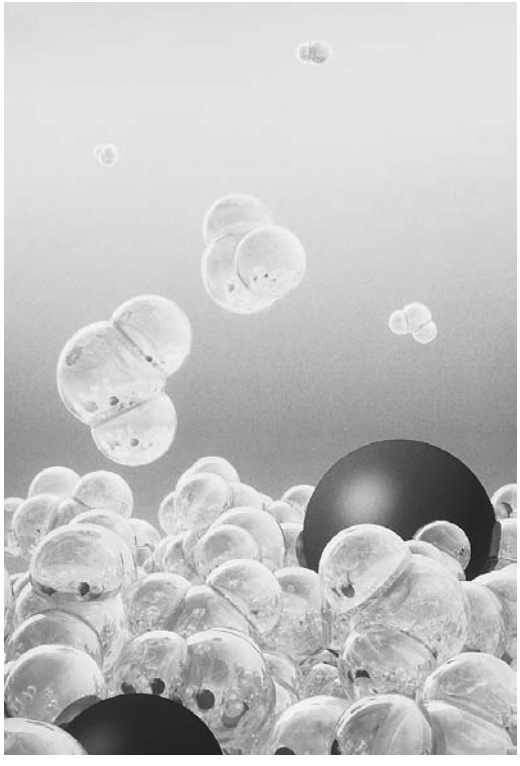
As we have noted, water and the hydrosphere are practically synonymous, but not completely so. The hydrosphere is the sum total of water on Earth, except for that portion in the atmosphere. This combines all water underground—which, as we shall see, constitutes the vast majority of water on the planet—as well as all freshwater in streams, rivers, and lakes; saltwater in seas and oceans; and frozen water in icebergs, glaciers, and other forms of ice (see Glaciology).

It is almost unnecessary to point out that water is essential to life. Human bodies, after all, are almost entirely made of water, and without water we would die much sooner than we would if we were denied food. Humans are not the only organisms dependent on water; whereas there are forms of life designated as *anaerobic,* meaning that they do not require oxygen, virtually nothing that lives can survive independent of water. Thus, the biosphere, which combines all living things and all recently deceased things, is connected intimately with the hydrosphere.

WATER ON EARTH. Throughout most of the modern era of scientific study—from the 1500s, which is to say most of the era of useful scientific study in all of human history—it has been assumed that water is unique to Earth. Presumably, if and when we found life on another planet, that planet also would contain water. But until that time, so it was assumed, we could be assured that the only planet with life was also the only planet with water.

In the latter part of the twentieth century, however, as evidence began to gather that Mars contains ice crystals on its surface, this exclusive association of water with Earth has been challenged. As it turns out, frozen water exists in several places within our solar system—as well it might, since water on Earth had to arrive from somewhere. It is believed, in fact, that water arrived on Earth at a very early stage, carried on meteors that showered the planet from space (see the entries Planetary Science and Sun, Moon, and Earth).

Since about three billion years ago, the amount of water on Earth has remained relatively constant. The majority of that water, however, is not in the biosphere, the atmosphere, or what we normally associate with the hydrosphere—



Water molecules evaporating from a solution. *(© K. Eward/Photo Researchers. Reproduced by permission.)*

that is, the visible rivers, lakes, oceans, and ice formations on Earth's surface. Rather, the largest portion of water on Earth is hidden away in the geosphere—that is, the upper portion of Earth's crust, on which humans live and from which we obtain the minerals and grow the plants that constitute much of the world we know.

Water Compartments in the Environment

In the course of circulating throughout Earth, water passes from the hydrosphere to the atmosphere. It does so through the processes of evaporation and transpiration. The first of these processes, of course, is the means whereby liquid water is converted into a gaseous state and transported to the atmosphere, while the second one—a less familiar term—is the process by which plants lose water through their stomata, small openings on the undersides of leaves. Earth scientists sometimes speak of the two as a single phenomenon, evapotranspiration.

Evaporation and transpiration, as well as the process whereby such moisture is returned to the solid earth—that is, precipitation—are discussed in the essay Evapotranspiration and Precipitation. Still, the atmosphere is just one of several "compartments" in which water is stored within the larger environment. Among the other important places in which water is found are the oceans and other surface waters, ice in its many forms, and aquifers. The latter are underground rock formations in which groundwater—water resources that occupy pores in bedrock—is stored.

Imbalances in the system. The total amount of water in all these compartments is fixed, but water moves readily between various compartments through the processes of evaporation, precipitation, and surface and subsurface flows. The hydrologic cycle is thus a system all its own, a "system" (in scientific terms) being any set of interactions that can be set apart mentally from the rest of the universe for the purposes of study, observation, and measurement. Its net input and output balance each other. There may be imbalances of input and output in particular areas, which will manifest as drought or flooding.

Flooding, as well as other aspects of the hydrosphere and its study, is discussed in the essay Hydrology. As for drought, its immediate cause is a lack of precipitation, though other causes can be responsible for the removal of water from the local environment. For instance, at present a large portion of Earth's water is tied up in glaciers and other ice formations, but at other times in the planet's history this ice has been melted, leaving much of the continental mass that we know today submerged under water (see Glaciology).

Accounting for Earth's water. Earth's total water supplies are so large that instead of being measured by gallons or other units of volume, they are measured in terms of tons or metric tons, designated as *tonnes.* Nonetheless, for comparison's sake, consider the following figures in light of the fact that a gallon (3.8 l) of water weighs 8.4 lb. (3.8 kg). A ton contains 238 gal., and a tonne has 1,000 l.

Just as heat from the Sun accounts for the lion's share of Earth's total energy budget (see Energy and Earth), the vast majority of water on Earth comes from the deep lithosphere, the upper layer of Earth's interior, comprising the crust and the brittle portion at the top of the mantle. In this vast region are contained 2.76×10^{19} tons (2.5×10^{19} tonnes). This figure, equal to 27.6 billion billion tons, is about 94.7% of the global total.

The next largest compartment is the oceans, which contain 1.41×10^{18} tons (1.38×10^{18} tonnes), or 5.2% of the total. Ice caps, glaciers, and icebergs contain 1.74×10^{16} tons (0.017×10^{16} tonnes), thus accounting for most of the remaining 0.1% of Earth's water. Beyond these amounts are much smaller quantities representing shallow groundwater (2.76×10^{14} tons, or 2.5×10^{14} tonnes); inland surface waters, such as lakes and rivers (2.76×10^{13} tons, or 2.5×10^{13} tonnes); and the atmosphere (1.43×10^{13} tons, or 1.3×10^{13} tonnes).

REAL-LIFE APPLICATIONS

The Life of a Water Droplet

Now let us follow the progress of a single water droplet as it passes through the water cycle. This particular droplet, like all others, has passed through the cycle countless times over the course of the past few billion years, and in its various incarnations it has existed as groundwater, as moisture in the atmosphere, and as ice.

For the short span of Earth's existence that humans have occupied the planet, it is conceivable that our droplet has been consumed—either directly, as liquid water, or indirectly, as part of the water content in animal or vegetable material. That would mean that it also has been excreted, after which it will have continued the cycle of circulation. In theory, it might well be part of the water in which humans bathe, brush their teeth, or wash their clothes.

WATER AND FOREIGN MATERIAL. Of course, personal hygiene as we know it today is an extremely recent development: for instance, regular toothbrushing as a practice among the whole population began in the United States only around the turn of the nineteenth century. Still, it is a bit disconcerting to think that the water in which we brush our teeth today may have floated down a sewer pipe at another time. Nonetheless, by moving water through so many locales, the hydrologic cycle has a built-in cleansing component.

This cleansing component can be illustrated by the experience of saltwater, which despite its presence in the ocean is actually a small portion of Earth's total water supply. The reason is that the salt seldom travels with the water; as soon as the water evaporates, the salt is left behind. This is why people on the proverbial desert island or in other survival situations use evaporation to make saltwater drinkable.

Likewise, saltwater as such cannot survive the transition from liquid water to ice: as the water freezes, the ice (which has a much lower freezing point) simply is precipitated and left behind. Just as salt does not travel with water as it makes its way through the various stages of the hydrologic cycle, so other varieties of foreign matter are left behind as well; as long as water is not allowed to stagnate, it usually is cleansed in the course of traveling between the ground and the atmosphere.

This is not to say that water typically exists in a pure form. Often called the *universal solvent,* water has such a capacity to absorb other substances that it is unlikely ever to appear in pure form unless it is distilled under laboratory conditions. Water in mountain streams, for instance, absorbs fragments of rock as it travels downhill, slowly eroding the surrounding rock and soil.

From the Watershed to Points Beyond

On a particular watershed—an area of terrain from which water flows into a stream, river, or lake—our hypothetical water droplet may enter from a number of directions. In the simplest model of water flow, it comes from precipitation, including rain, snow, or even mist from clouds. The water has to go somewhere, and it may go either up or down. It may return to the atmosphere as evapotranspiration; it may enter the ground; or, if it reaches the solid earth at some elevation above sea level, it may enter a stream and flow ultimately to the ocean.

For water to enter the atmosphere generally requires an extensive surface area of vegetation, which supports high rates of transpiration. This transpiration, combined with evaporation from such inorganic surfaces as moist soil or bodies of water, puts a great deal of water into the atmosphere. Without significant evapotranspiration, however, it is necessary for the water to drain from the watershed, either as seepage to deep groundwater or as flow in the form of a stream.

THE FIVE STAGES OF THE HYDROLOGIC CYCLE. The overall process of the hydrologic cycle can be divided into five parts: condensation, precipitation, infil-



The Arkansas River, part of the Ogallala Aquifer, runs through irrigated fields in Kansas. Irrigation places a big demand on the Ogallala's diminishing water supply. *(AP/Wide World Photos. Reproduced by permission.)*

tration, runoff, and evaporation. Water vapor in the atmosphere condenses, forming clouds, which eventually become so saturated that they release the water to the solid earth in the form of precipitation. When precipitation enters the ground, it is known as infiltration.

Infiltration can be great or small, depending on the permeability of the ground. The soil of a

rainforest, for instance, has so much organic matter that it is likely to be highly permeable. On the other hand, cities have large amounts of what land developers call impervious surface: roads, buildings, and other areas in which concrete and other materials prevent water from infiltrating the ground.

Assuming that water is unable to infiltrate, it becomes runoff. Runoff is simply surface water, which may take the form of streams, rivers, lakes, and oceans. If runoff occurs in an area that is not already a body of water, flood conditions may ensue. Thus, water may either infiltrate or become runoff, but as long as it remains close to the surface, it will experience evaporation.

In evaporation energy from the Sun changes liquid water into gaseous form, transporting it as a vapor into the atmosphere. Thus, the water is returned to the air, where it condenses and resumes the cycle we have described. As noted earlier, the water on or near Earth's surface is a small portion of the total. What about groundwater far below the surface? Let us now examine a particularly notable example of an aquifer, or groundwater reservoir.

THE OGALLALA AQUIFER

Located beneath the central United States, the Ogallala Aquifer provides a vast store of groundwater that supports a large portion of American agriculture. The Ogallala, also known as the High Plains Regional Aquifer, was discovered in the early years of the nineteenth century. It did not become a truly significant economic resource, however, until the second half of the twentieth century, when advanced pumping technology made possible large-scale irrigation from the aquifer's supplies. By 1980 the Ogallala supported some 170,000 wells and accounted for fully one-third of all water used for irrigation purposes in the United States.

Centered in Nebraska, the aquifer underlies parts of seven other states: South Dakota, Wyoming, Colorado, Kansas, Oklahoma, Texas, and New Mexico. It stretches 800 mi. (1,287 km) from north to south and 200 mi. (322 km) from east to west at its widest point. All told, the Ogallala covers some 175,000 sq. mi. (453,250 sq km), an area larger than Germany—all of it underground.

In Nebraska, the aquifer is between 400 ft. and 1,200 ft. (130–400 m) deep, while at the southern edges its depth extends no more than 100 ft. (30 m). Composed of porous sand, silt, and clay formations deposited by wind and water from the Rocky Mountains, the Ogallala is made up of several sections, called formations. The largest of these is the Ogallala formation, which accounts for about 77% of its total volume.

USING UP THE OGALLALA. The Ogallala is particularly important to local agriculture because the states that it serves are home to numerous dry areas. Yet high-volume pumping of the underground reserves has reduced the available groundwater, much as the pumping of oil gradually is consuming Earth's fossil-fuel reserves. Indeed, the water of the Ogallala is known as fossil water, meaning that it has been stored underground for millions of years, just as the coal, oil, and gas that runs modern industrial civilization has.

Of course, the water from the Ogallala is not simply used up in an irreversible process, as is the case with fossil fuels; nonetheless, the rapidly accelerating reduction of its water supplies is cause for some alarm. Less than 0.5% of the water removed from this aquifer is being returned to the ground, and if the current rate of pumping increases, the supplies will be 80% depleted by 2020.

The consequences of this depletion are already being felt in Kansas, where streams and rivers, dependent on groundwater to feed their flow, are running dry. In that state alone, more than 700 mi. (1,126 km) of rivers that formerly flowed year-round have been reduced to dry channels. In New Mexico and Texas, use of center-pivot irrigation, which requires a well capable of pumping 750 gal. (2,839 l) per minute, is disappearing because the local aquifer can no longer sustain such volumes.

In addition to the problem of diminishing supplies, contamination is an issue. As more and more agricultural chemicals seep into an ever shrinking reservoir, the towns of the high plains—places once known for their pure, clean groundwater—now have tap water that is considered unsafe for children and pregnant women. Overuse of the Ogallala is also exacting a financial toll, as more and more wells run dry and farms go bankrupt.

KEY TERMS

AQUIFER: An underground rock formation in which groundwater is stored.

BEDROCK: The solid rock that lies below the C horizon, the deepest layer of soil.

BIOSPHERE: A combination of all living things on Earth—plants, mammals, birds, reptiles, amphibians, aquatic life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

EVAPORATION: The process whereby liquid water is converted into a gaseous state and transported to the atmosphere.

EVAPOTRANSPIRATION: The loss of water to the atmosphere via the processes of evaporation and transpiration.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

GROUNDWATER: Underground water resources that occupy the pores in bedrock.

HYDROLOGIC CYCLE: The continuous circulation of water throughout Earth and between various earth systems.

HYDROLOGIC SCIENCES: Areas of the earth sciences concerned with the study of the hydrosphere. Among these areas of study are hydrology, glaciology, and oceanography.

HYDROLOGY: The study of the hydrosphere, including the distribution of water on Earth, its circulation through the hydrologic cycle, the physical and chemical properties of water, and the interaction between the hydrosphere and other earth systems.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

LITHOSPHERE: The upper layer of Earth's interior, including the crust and the brittle portion at the top of the mantle.

PRECIPITATION: When discussing the hydrologic cycle or meteorology, precipitation refers to the water, in liquid or solid form, that falls to the ground when the atmosphere has become saturated with moisture.

SYSTEM: Any set of interactions that can be set apart mentally from the rest of the universe for the purposes of study, observation, and measurement.

TRANSPIRATION: The process whereby plants lose water through their stomata, small openings on the undersides of leaves.

WATERSHED: An area of terrain from which water flows into a stream, river, lake, or other large body.

RIVERS

Despite the environmental challenges posed by such situations as the exhaustion of the Ogallala, the hydrologic cycle continues to roll on. As it does, it is sustained in large part by processes we cannot see: the movement of groundwater from the aquifer into streams or the evapotranspiration of surface waters to the atmosphere. Yet the movement of waters along the surface, because it is visible and recognizable to humans, attracts human attention in a way that many of these other components of the hydrologic cycle do not.

Rivers and other forms of surface water actually account for a relatively small portion of the planet's water supply, but they loom large in the human imagination as the result of their impact on our lives. The first human civilizations developed along rivers in Egypt, Mesopotamia, India, and China, and today many a great city lies along a river. Rivers provide us with a means of transportation and recreation, with hydroelectric power, and even—after the river water has been treated—with water for drinking and bathing.

FORMATION OF RIVERS. Rivers usually form from tributaries, such as springs. As the river flows, it is fed by more tributaries and by groundwater and continues on its way at various speeds, depending on the terrain. Finally, the river discharges into an ocean, a lake, or a desert basin.

River waters typically begin with precipitation, whether in the form of rainwater or melting snow. They also are fed by groundwater exuding from bedrock to the surface. When precipitation falls on ground that is either steeply sloped or already saturated, the runoff moves along Earth's surface, initially in an even, paper-thin sheet. As it goes along, however, it begins to form parallel rills, and its flow becomes turbulent. As the rills pass over fine soil or silt, they dig shallow channels, or runnels.

At some point in their flow, the runnels merge with one another, until there are enough of them to form a stream. Once enough streams have converged to create a continuously flowing body of water, it becomes a brook, and once the volume of water carried reaches a certain level, the brook becomes a river. As we have already noted, however, a river is really the sum of its tributaries, and thus hydrologists speak of river *systems* rather than single rivers.

RIVER SYSTEMS. A particularly impressive example of a river system is the vast Mississippi-Missouri, which drains the central United States. Most of the rivers between the Rockies and the Appalachians that do not empty directly into the Gulf of Mexico feed this system. This system includes the Ohio, itself an impressive river that divides the eastern United States. Indeed, just as the Mississippi separates east from west in America, the Ohio separates north from south.

After the Ohio and the Mississippi converge, at the spot where Illinois, Missouri, and Kentucky meet, they retain their separate identities for many miles. A strip of clear water runs along the river's eastern side, while to the west of this strip the water is a cloudy yellow—indicating a heavier amount of sediment in the Mississippi than in the Ohio. A similar phenomenon occurs where the "Blue Nile" and "White Nile," tributaries of another great river—both named for the appearance of the water—meet at Khartoum in Sudan.

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GLACIOLOGY

CONCEPT

Glaciology is the study of ice and its effects. Since ice can appear on or in the earth as well as in its seas and other bodies of water and even its atmosphere, the purview of glaciologists is potentially very large. For the most part, however, glaciologists' attention is direction toward great moving masses of ice called glaciers, and the intervals of geologic history when glaciers and related ice masses covered relatively large areas on Earth. These intervals are known as ice ages, the most recent of which ended on the eve of human civilization's beginnings, just 11,000 years ago. The last ice age may not even be over, to judge from the presence of large ice masses on Earth, including the vast ice sheet that covers Antarctica. On the other hand, evidence gathered from the late twentieth century onward indicates the possibility of global warming brought about by human activity.

HOW IT WORKS

Ice

Ice, of course, is simply frozen water, and though it might appear to be a simple subject, it is not. Glaciologists classify differing types of ice, for instance, with regard to their levels of density, designating them with Roman numerals. The ice to which most of us are accustomed is classified as ice I. We will not be concerned with the other varieties of ice in the present context, but it should be noted that the ice in glaciers is quite different from the ice in an ice cube or even the ice on a pond in winter. These differences are a result of massive pressure, which reduces the air content of the ice in glaciers.

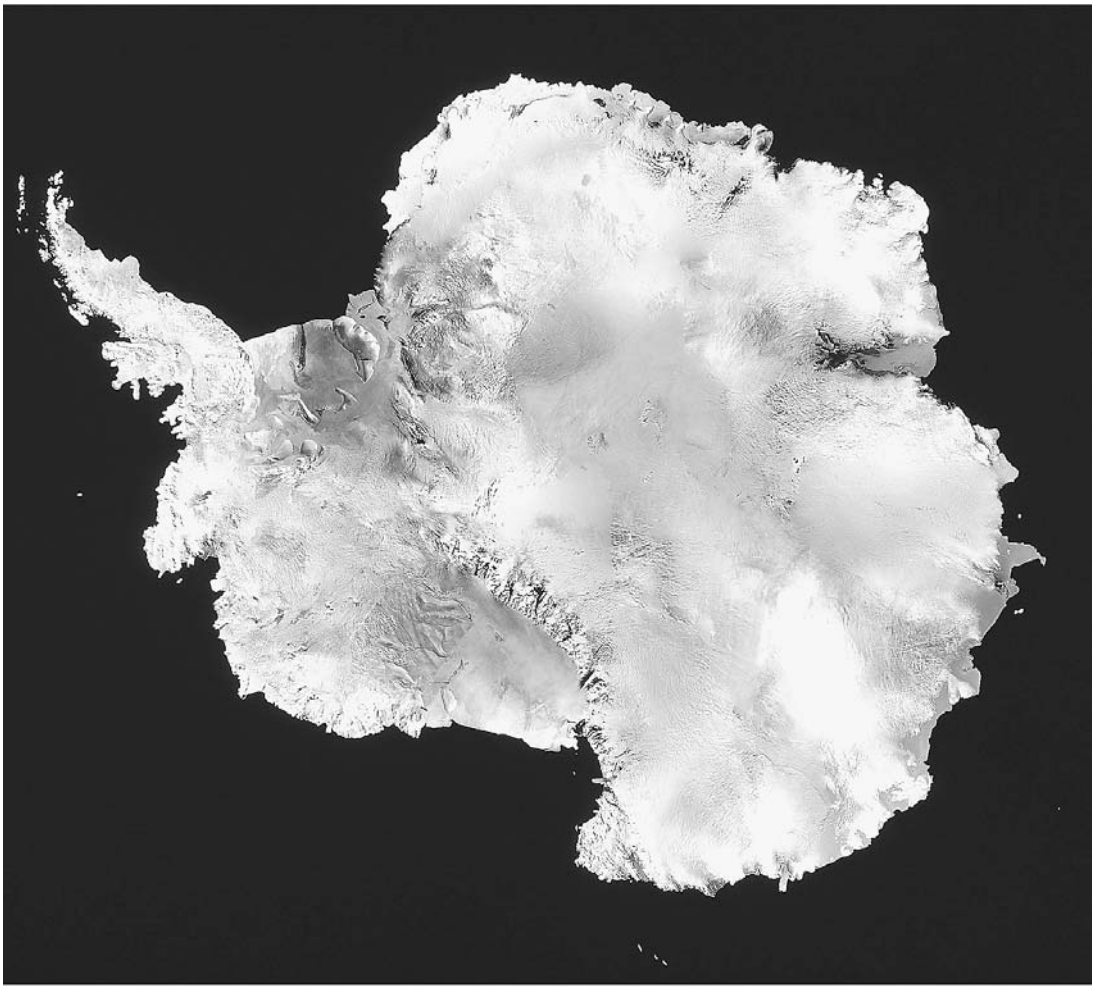
By definition, ice is composed of fresh water rather than saltwater. This is true even of icebergs, though they may float on the salty oceans. The reason is that water has a much higher freezing point than salt, and, therefore, when water freezes, very little of the salt remains joined to the water. Most of the salt is left behind in the form of a briny slush, and so much of Earth's fresh water supply actually is contained in great masses of ice, such as the glaciers of Antarctica.

Glaciology is defined as the study of ice, its forms, and its effects. This means that the glaciologist has a much wider scope than a geologist, meteorologist, or oceanographer, each of whom is concerned primarily with the geosphere, atmosphere, and hydrosphere, respectively. Though ice commonly is associated with the hydrosphere, where it appears on Earth's oceans, rivers, and lakes, it also is found on and even under the solid earth. There are even situations in which ice is found in the atmosphere.

Glaciology and Glaciers

Despite the wide distribution of ice on Earth and the many forms it takes, the work of most glaciologists is concerned primarily with ice as it appears in glaciers. A glacier is a large, typically moving mass of ice on or adjacent to a land surface. It does not flow, as water does; rather, it is moved by gravity, a consequence of its extraordinary weight.

Obviously, a glacier can form only in an extremely cold region—one so cold that the temperature never becomes warm enough for snow to melt completely. Some snow may melt as a result of contact with the ground, which is likely to be warmer than the snow itself, but when tem-



An infrared satellite image of Antarctica, showing ice shelves projecting from the coastline. The largest ice shelf, the Ross, sits to the left of the Transantarctic Mountains (lower center). *(© USGS/Photo Researchers. Reproduced by permission.)*

peratures drop, it refreezes. A glacier starts with a layer of ice, on which snow gathers until refreezing gradually creates compacted layers of snow and ice.

As anyone who has ever held a snowball in his or her hand knows, snow is fluffy, or, to put it in more scientific terms, it is much less dense than ice. A sample of snow is about 80% air, but as ice accumulates over a layer of snow, the weight of the ice squeezes out most of the air. As the layers grow thicker and thicker, the weight reduces the air further, creating an extremely dense, thick layer of ice. Ultimately, the ice becomes so heavy that its weight begins to pull it downhill, at which point it becomes a glacier.

Glacial Temperature and Morphologic Characteristics

Glaciers may be classified according to either relative temperature or morphologic characteristics (i.e., in terms of its shape). In terms of temperature, a glacier may be "warm," meaning that it is close to the pressure melting point. *Pressure melting point* is defined as the temperature at which ice begins to melt under a given amount of pressure. It is commonly known that water melts at 32°F (0°C), but only under conditions of ordinary atmospheric pressure at sea level. At higher pressures, the melting point of water is lower, which means that it can remain liquid at temperatures below its ordinary freezing point. (The

melting point and freezing point of a substance are always the same.)

A "warm" glacier, such as those that appear in the Alps, is relatively mobile, because it is at the pressure melting point. This kind of glacier contrasts with a "cold," or polar, glacier, in which the temperatures are well below the pressure melting point; in other words, despite the extremely high pressure, the temperature is so low that the ice will not melt. As their name suggests, polar glaciers are found at Earth's poles, which effectively means Antarctica, since the area of the North Pole is not a land surface. A third category of glacier, in terms of temperature, is a subpolar glacier, found (not surprisingly) in regions near the poles. Examples of subpolar glaciers, or ones in which the fringes of the glacier are colder than the interior, are found in Spitsbergen, islands belonging to Norway that sit in the Arctic Ocean, well to the north of Scandinavia.

Morphologic classifications. In the classification of geologic sciences, glaciology often is grouped with geomorphology. The latter field of study is devoted to landforms, or notable topographical features, and the forces and processes that have shaped them. Among those forces and processes are glaciers, which can be viewed in terms of their shape, the locale in which they form, and their effect on the contour of the land.

Alpine or mountain glaciers flow down a valley from a high mountainous region, typically following a path carved out by rivers or melting snow in warmer periods. They move toward valleys or the ocean, and in the process they exert considerable impact on the surrounding mountains, increasing the sharpness and steepness of these landforms. The rugged terrain in the vicinity of the Himalayas and the Andes, as well as the alpine regions of the Cascade Range and Rocky Mountains in the United States, are partly the result of weathering caused by these glaciers.

The glacial forms found in Alaska, Greenland, Iceland, and Antarctica are often piedmont glaciers, large mounds of ice that slope gently. Iceland, Greenland, and Antarctica as well as Norway are also home to cirque glaciers, which are relatively small and wide in proportion to their length. Though they experience considerable movement in place, they usually do not move out of the basinlike areas in which they are formed.

Other Ice Formations

There are several other significant varieties of ice formation, including ice caps, ice fields, and ice sheets. An ice cap, though much bigger than a glacier, typically has an area of less than 19,300 sq. mi. (50,000 sq km). Nonetheless, its mass is such that it exerts enormous weight on the land surface, and this exertion of force allows it to flow.

At the center of an ice cap or an ice sheet is an ice dome, and at the edges are ice shelves and outlet glaciers. Symmetrical and convex (i.e., like the outside of a bowl), an ice dome is a mass of ice often thicker than 9,800 ft. (3,000 m). An outlet glacier is a rapidly moving stream of ice that extends from an ice dome. Ice shelves, at the far outer edges, extend into the oceans, typically ending in cliffs as high as 98 ft. (30 m). Ice fields are similar to ice caps; the main difference is that the ice field is nearly level and lacks an ice dome. There are enormous variations in size for ice fields. Some may be no larger than 1.9 sq. mi. (5 sq km), while at different times in Earth's history, others have been as large as continents.

The most physically impressive of all ice formations, an ice sheet is a vast expanse of ice that gradually moves outward from its center. Ice sheets are usually at least 19,300 sq. mi. (50,000 sq km) and, like ice caps, consist of ice domes and outlet glaciers, with outlying ice shelves. Given their even greater size compared with ice caps, ice sheets exert still more force on the solid earth beneath them. They cause the rock underneath to compress, and, therefore, if an ice sheet ever melts, Earth's crust actually will rise upward in that area.

Real-Life Applications

Antarctica

An example of an ice sheet is the Antarctic ice sheet, which is permanently frozen—at least for the foreseeable future. The Antarctic ice sheet covers most of Antarctica, an area of about five million sq. mi. (12.9 million sq km), the size of the United States, Mexico, and Central America combined. Within it lies 90% of the world's ice

and more fresh water than in all the planet's rivers and lakes combined. By contrast, the impressive Greenland ice sheet, at 670,000 sq. mi. (1,735,000 sq km), is dwarfed, as are smaller ice sheets in Iceland, northern Canada, and Alaska.

The Antarctic ice sheet is the Sahara of ice masses, though, in fact, it is almost 50% larger than the Sahara desert and a good deal more inhospitable. Whereas the Sahara is scattered with towns and oases and has a steady population of isolated villagers, nomads, and merchants in caravans, *no one* lives on the Antarctic ice sheet except scientists on temporary missions. And whereas people have lived in the Sahara for thousands of years (it became a desert only somewhat recently, during the span of human civilization), scientific missions to Antarctica became possible only in the twentieth century. As it is, researchers spend only short periods of time on the continent and then in heavily protected environments.

ICE SHELVES AND GLACIERS. Just as the Antarctic ice sheet is the largest in the world, one of its attendant shelves also holds first place among ice shelves. The continent is shaped somewhat like a baby chick, with its head and beak pointing northward toward the Falkland Islands off the coast of South America and its two greatest ice shelves lying on either side of the "neck."

Facing the Weddell Sea, and the southern Atlantic beyond it, is the Ronne Ice Shelf, which extends about 400 mi. (640 km) over the water. The world record–holder, however, is the Ross Ice Shelf on the other side of the "neck," near Marie Byrd Land. About the same size as Texas or Spain, the Ross shelf extends some 500 mi. (800 km) into the sea and is the site of several permanent research stations.

ANTARCTIC TOPOGRAPHY. The Antarctic is also home to a vast mountain range, the Transantarctic, which stretches some 3,000 mi. (4,828 km) across the "neck" between the Ross and Weddell seas. Included in the Transantarctic Mountains is Vinson Massif, which at 16,860 ft. (5,140 m) is the highest peak on the continent. The continent as a whole is largely covered with mountain ranges, between which lie three great valleys called the Wright, Taylor, and Victoria valleys. Each is about 25 mi. (40 km) long and 3 mi. (5 km) wide.

These are the largest continuous areas of ice-free land on the continent, and they offer rare glimpses of the rocks that form the solid-earth surface deep beneath Antarctica. They are also among the strangest places on the planet, forbidding lands even by Antarctic standards. The three are known as the "dry valleys," owing to their lack of precipitation; indeed, if they lay in a more temperate zone, they would be deserts far more punishing than the Sahara. Geologists estimate that it has not rained or snowed in these three valleys for at least one million years. The reason is that ceaseless winds keep the air so dry that any falling snow evaporates before it reaches the ground. In this arid, brutally cold climate, nothing decomposes, and seal carcasses a millennium old remain fully intact.

THE THICKNESS OF THE ICE. The dry valleys are exceptional, because most of Antarctica lies under so much ice that the rocks cannot be seen. The ice in Antarctica has an *average* depth of more than a mile: the depth averages about 6,600 ft. (2,000 m), but in places on the continent it is as thick as 2 mi. (3.2 km). Thus, "ground level" on Antarctica is equivalent to a fairly high elevation in the inhabitable portion of the planet. Denver, Colorado, for instance, touts itself as the "Mile-High City," and its elevation has enough effect on a visiting flatlander that rival sports teams usually spend a few days in Denver before a game, adjusting themselves to the altitude.

The thickness of the ice has allowed glaciologists to take deep ice-core samples from Antarctica. An ice core is simply a vertical section of ice that, when studied with the proper techniques and technology, can reveal past climatic conditions in much the same way that the investigation of tree rings does. (See Paleontology for more about tree-ring research, or dendrochronology.) Ice-core samples from the Antarctic provide evidence regarding Earth's climate for the past 160,000 years and show a pattern of warming and cooling that is related directly to the presence of carbon dioxide and methane in the atmosphere. These core samples also reveal the warming effects of increases in both gases over the past two centuries.

Because of the great thickness of its ice, Antarctica has the highest average elevation of any continent on the planet. Yet beneath all that ice, the actual landmass is typically well below sea level. The reason for this is that the ice weighs it down so much; by contrast, if the ice were to

melt, the land would begin to spring upward. The melting of the Antarctic ice shelf would be a disaster of unparalleled proportions. If all that ice were to melt at once, it would raise global sea levels by some 200 ft. (65 m). This would be enough to flood all the world's ports, along with vast areas of low-lying land. For instance, waters would swell over New York City and all ports on America's eastern seaboard and probably would cover an area extending westward to the Appalachian Mountains. Even if only 10% of Antarctica's ice were to melt, the world's sea level would rise by 20 ft. (6 m), enough to cause considerable damage.

What Glaciers Do to Earth's Surface

Periodically over the past billion years, Earth's sea levels have advanced or retreated dramatically in conjunction with the beginning and end of ice ages. The latter will be discussed at the conclusion of this essay; in the present context, let us consider simply the geomorphologic effects of glaciers and ice masses. For example, as suggested in the discussion of Antarctica's ice sheet, when glaciers melt, thus redistributing their vast weight, Earth's crust rebounds. At the end of the last ice age, the crust rose upward, and in parts of North America and Europe this process of crustal rebounding is still occurring.

Glaciers move at the relatively slow speeds one would expect of massive objects made from ice: only a few feet or even a few inches per day. Friction with Earth's surface may melt the layer of ice that comes in contact with it, however, and, as a result, this layer of meltwater becomes like a lubricated surface, allowing the glacier to move much faster. The entire body of ice experiences a sudden increase of speed, called surging.

Plowing through the land. A glacier is like a huge bulldozer, plowing though rock, soil, and plants and altering every surface with which it comes into contact. It erodes the bottoms and sides of valleys, changing their V shape to a U shape. The rate at which it erodes the land is directly proportional to the depth of the glacier: the thicker the ice, the more it bears down on the land below it. As it moves, the ice pulls along rocks and soil, which are incorporated into the glacier itself. These components, in turn, make the glacier even more formidable, giving it greater weight, cutting ability, and erosive power.

The sediments left by glaciers that lack any intervening layer of melted ice are known by the general term till. In unglaciated areas, or places that have never experienced any glacial activity, sediment is formed by the weathering and decomposition of rock. On the other hand, formerly glaciated areas are distinguished by layers of till from 200 to 1,200 ft. (61–366 m) thick. Piles of till left behind by glaciers form hills called moraines, and the depressions left by these land-scouring ice masses are called kettle lakes.

North America abounds with examples of moraines and kettle lakes. Illinois, for instance, is covered with ridges, called end moraines, left behind by the melting near the conclusion of the last ice age. Visitors can take in a splendid view of moraine formations at Moraine View State Recreation Area, located astride the Bloomington moraine in central Illinois. Likewise Minnesota, Wisconsin, the Dakotas, and Wyoming are home to many a moraine. As with the Illinois recreation area, Kettle Lakes Provincial Park, near Timmins, Ontario, provides an opportunity to glimpse gorgeous natural wonders left behind by the retreat of glaciers—in this case, more than 20 deep kettle lakes. Park literature invites visitors to boat, fish, or swim in the lakes, though it would take a hardy soul indeed to brave those icy waters.

The glacier transports material from the solid earth as long as it is frozen, but wholly or partially melted glaciers leave behind sedimentary forms with their own specific names. In addition to moraines, there are piles of sediment, called eskers, left by rivers flowing under the ice. In addition, deposits of sediment may wash off the top of a glacier to form steep-sided hills called kames. If the glacier runs over moraines, eskers, or kames left by another glacier, the resulting formation is called a drumlin.

Just as rivers consist of main bodies formed by the flow of tributaries (for example, the many creeks and smaller rivers that pour into the Mississippi), so there are tributary glaciers. When a glacial tributary flows into a larger glacier, their top elevations become the same, but their bottoms do not. As a result, they carve out "hanging valleys," often the site of waterfalls. Examples include Yosemite and Bridalveil in California's Yosemite Valley.



The Kennicott glacier in the Wrangell Mountains of Alaska. *(© Pat and Tom Leeson/Photo Researchers. Reproduced by permission.)*

Ice Ages

The glaciers that exist today are simply the remnants of the last ice age, a time in which the size of the ice masses on Earth dwarfed even the great Antarctic ice sheet. When people speak of "the Ice Age," what they mean is the *last* ice age, which ended about 11,000 years ago. Yet it is one of only about 20 ice ages that have taken place over the past 2.5 million years, roughly coinciding with the late Pliocene and Pleistocene epochs. Actually, periods of massive glaciation (the covering of the landscape with large expanses of ice) have occurred at intervals over the past billion years. Their distribution over time has not been random; rather, they are concentrated at specific junctures in Earth's history.

Like the great mass extinctions of the past (see Paleontology), ice ages are among the markers geologists use in separating one interval of geologic time from another. In fact, there have been connections between ice ages and mass extinctions, particularly those that resulted from a recession of the seas. For example, the mass extinction that took place near the end of the Ordovician period (about 435 million years, or Ma, ago) came about as a result of a drop in the ocean level, which was caused, in turn, by an increase of glaciation that coincided with that phase in Earth's history.

The late Ordovician/early Silurian ice ages (between 460 to 430 Ma ago) are among four major phases of glaciation during the past 800

KEY TERMS

ATMOSPHERE: In general, an atmosphere is a blanket of gases surrounding a planet. Unless otherwise identified, however, the term refers to the atmosphere of Earth, which consists of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon, which together comprise 0.07%.

CRUSTAL REBOUNDING: An upward movement by Earth's crust in response to the melting of a glacier, which redistributes its vast weight and causes Earth to rebound.

GEOMORPHOLOGY: An area of physical geology concerned with the study of landforms, with the forces and processes that have shaped them, and with the description and classification of various physical features on Earth.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid Earth on which human beings live and that provides them with most of their food and natural resources.

GLACIATION: The covering of the landscape with large expanses of ice, as during an ice age.

GLACIER: A large, typically moving mass of ice on or adjacent to a land surface.

GLACIOLOGY: An area of physical geology devoted to the study of ice, its forms, and its effects.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

ICE AGE: A period of massive and widespread glaciation. Ice ages usually occur in series over stretches of several million years, or even several hundred million years.

ICE CAP: An ice formation bigger than a glacier but smaller than an ice sheet. An ice cap typically has an area of less than 19,300 sq. mi. (50,000 sq km) and, like an ice sheet, consists of an ice dome, with ice shelves and outlet glaciers at the edges.

ICE CORE: A vertical section of ice, usually taken from a deep ice sheet such as that in Antarctica. When studied with the proper techniques and technology, ice cores can reveal past climatic conditions in much the same way that the investigation of tree rings does.

ICE DOME: A symmetrical, convex (i.e., like the outside of a bowl) mass of ice, often thicker than 9,800 ft. (3,000 m), usually found at the center of an ice cap or an ice sheet.

million years. The first of these occurred during the late Proterozoic eon, toward the end of Precambrian time (between 800 and 600 Ma ago). Another happened during the Pennsylvanian subperiod of the Carboniferous and extended throughout the Permian period, thus lasting from about 350 to 250 million years ago. The last period of glaciation is the one in which we are living, beginning in the late Neogene period and extending into the current Quaternary.

HUMANS AND THE ICE AGES. In fact, many scientists question whether the last ice age has ended and whether we are merely living in an interglacial period. Certainly crustal rebounding is still taking place, as noted earlier.

KEY TERMS CONTINUED

ICE FIELD: A large ice formation, similar to an ice cap except that it is nearly level and lacks an ice dome. There are enormous variations in size for ice fields. Some may be no larger than 1.9 sq. mi. (5 sq km), while at different times in Earth's history, some have been as large as continents.

ICE SHEET: A vast expanse of ice, usually at least 19,300 sq. mi. (50,000 sq km), that moves outward from its center. Like the smaller ice caps, ice sheets consist of ice domes and outlet glaciers, with outlying ice shelves.

ICE SHELF: An ice formation at the edge of an ice cap or ice sheet that extends into the ocean, typically ending in cliffs as high as 98 ft. (30 m).

LANDFORM: A notable topographical feature, such as a mountain, plateau, or valley.

MA: An abbreviation used by earth scientists, meaning million years or megayears. When an event is designated as, for instance, 160 Ma, it usually means 160 million years ago.

MASS EXTINCTION: A phenomenon in which numerous species cease to exist at or around the same time, usually as the result of a natural calamity.

MORAINE: A hill-like pile of till left behind by a glacier.

MORPHOLOGY: Structure or form, or the study thereof.

OUTLET GLACIER: A rapidly moving stream of ice that extends from an ice dome.

PHYSICAL GEOLOGY: The study of the material components of Earth and of the forces that have shaped the planet. Physical geology is one of two principal branches of geology, the other being historical geology.

PRESSURE MELTING POINT: The temperature at which ice begins to melt under a given amount of pressure. The higher the pressure, the lower the temperature at which water can exist in liquid form.

RELIEF: Elevation and other inequalities on a land surface.

SEDIMENT: Material deposited at or near Earth's surface from a number of sources, most notably preexisting rock.

TILL: A general term for the sediments left by glaciers that lack any intervening layer of melted ice.

TOPOGRAPHY: The configuration of Earth's surface, including its relief as well as the position of physical features.

Inasmuch as "glacial period" refers to a time when glaciers cover significant portions of Earth and when the oceans are not at their maximum levels, we are indeed still in a glacial period.

It seems as though human existence has been bounded by ice, both in its onset and its recession. Ice ages have been a regular feature of the two million years since *Homo sapiens* came into existence, and the species had much of its formative experience in times of glaciation. The latter part of the last ice age created a land bridge that made possible the migration of Siberian peoples to the Americas, so that they are known now as *Native Americans.* (The name is well deserved: the ancestors of the Native Americans

moved east from Siberia about 12,000 years ago, whereas less than half that much time has elapsed since the Indo-European ancestors of Caucasian Europeans moved west from what is now Russia. Certainly no one today questions whether Germans, Italians, British, French, and other groups are "native" Europeans.)

As an indication that ice ages have not ceased to occur, there is the Little Ice Age, which lasted from as early as 1250 to about 1850. This was a period of cooling and expansion of glaciers in the temperate latitudes on which Europe is located. Glaciers destroyed farmlands and buildings in the Alps, Norway, and Iceland, while Norse settlements in Greenland became uninhabitable. Europe as a whole suffered widespread crop failures, with a resulting loss of life. Evidence for this ice age, and indeed for all ice ages, can be discerned from the "footprints" left by glaciers from that time. Another telling sign is the transport of materials, such as rocks and fossils, from one part of Earth's surface to another.

UNDERSTANDING ICE AGES. What caused the Little Ice Age? The answer, or rather the attempt at an answer, goes to the core question of what causes ice ages in general. Earth scientists have cited both extraterrestrial and terrestrial factors. Among the leading extraterrestrial causes are an increase in sunspot activity (see Sun, Moon, and Earth for more about sunspots) as well as changes in Earth's orientation with respect to the Sun.

Contenders for a terrestrial explanation include changes in ocean circulation, as well as meteorites and volcanism. Either of these last two could have caused the atmosphere to become glutted with dust, choking out the Sun's light and cooling the planet considerably. (Such a calamity has been blamed for several instances of mass extinction, most notably, the one that wiped out the dinosaurs some 65 million years ago. See Paleontology.)

THE FUTURE. Though it appears that we are living in an interglacial period and that Earth could undergo significant cooling again thousands of years from now, there is also an even more frightening prospect of human-induced *warming.* As noted earlier, the Antarctic ice core reveals an increase of carbon dioxide and methane in the atmosphere during the past two centuries. Though these gases can be produced naturally, this excess in recent times appears to be a by-product of industrialized society. The glaciers of Europe are receding, and whether this could be the result of human activity or simply part of Earth's natural change as it comes out of the last ice age remains to be seen.

In the meantime, ice offers a great deal of potential for understanding our own planet and others. It may yet turn out that the ice sheets covering Mars contain single-cell life-forms. Furthermore, in August 1996, the National Aeronautics and Space Administration (NASA) reported that a meteorite found on the Antarctic ice may provide evidence of life on Mars. It seems that the 4.1-lb. (2 kg) meteorite contains polycyclic aromatic hydrocarbons that may have existed on that planet several billion years ago.

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METEOROLOGY AND THE ATMOSPHERE

EVAPOTRANSPIRATION AND PRECIPITATION

WEATHER

CLIMATE

EVAPOTRANSPIRATION AND PRECIPITATION

CONCEPT

Evaporation, along with the less well known process of transpiration, is the means by which water enters the atmosphere in the form of moisture. In evaporation liquid water from nonliving sources, such as the soil and surface waters, is converted into a gas. This conversion is driven by the power of the Sun, whose energy is also behind the process of transpiration, whereby plants lose water through their leaves. As with evaporation, transpiration places water in the atmosphere, and because the two processes work in tandem, they usually are spoken of together under the name evapotranspiration. Both make possible the formation of clouds, which, when they become saturated with moisture, produce the forms of precipitation by which water returns to the solid earth.

HOW IT WORKS

The Movement of Water

The hydrosphere is the sum total of Earth's water, with the exception of water in the atmosphere. The hydrologic cycle is the continuous circulation between these two earth systems, hydrosphere and atmosphere, as well as the two other principal earth systems, biosphere and geosphere (see Earth Systems). Evapotranspiration and precipitation are principal components of this cycle, which is discussed in depth within the Hydrologic Cycle essay.

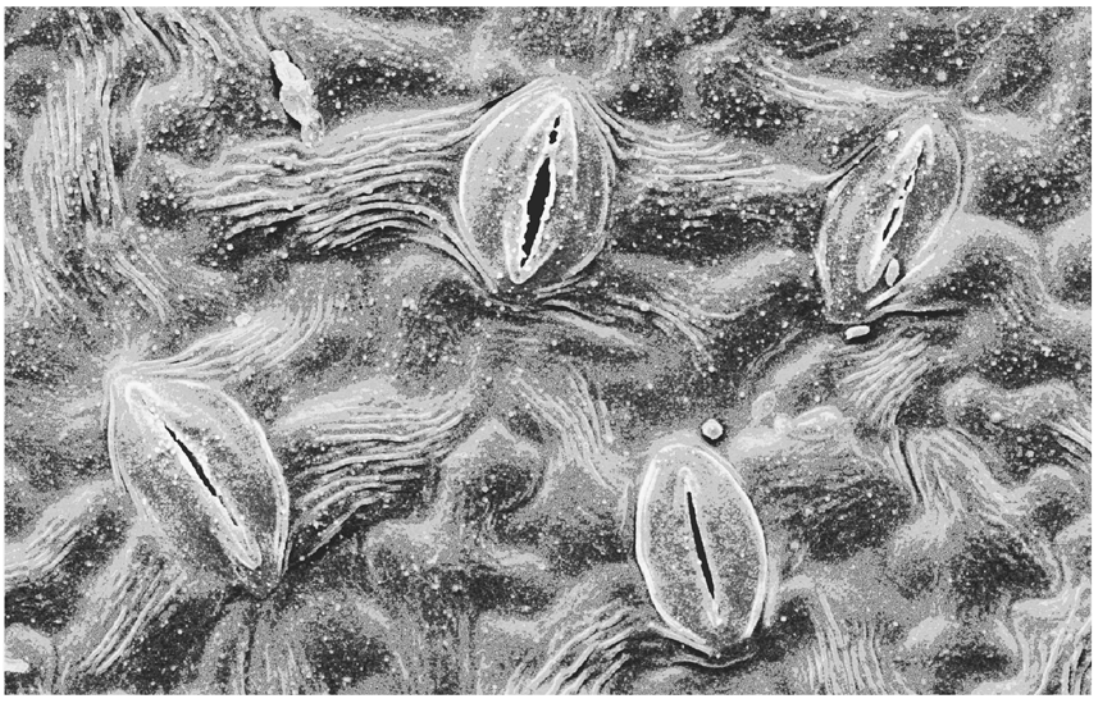
In evaporation, heat converts liquid water to a gaseous state, thus allowing it to be transferred to the atmosphere in the form of vapor. Whereas evaporation involves the loss of water to the atmosphere from nonliving sources, transpiration is the movement of water from living organisms to the atmosphere. This is achieved by the release of water through the plants' stomata, small openings on the undersides of leaves. In both cases, the Sun's electromagnetic energy, experienced as heat, is the driving mechanism, and because these phenomena are so closely related, they are normally treated together as evapotranspiration.

Earth's Water Budget

Our present concern is primarily with the atmosphere; nonetheless, it is important to consider the other "compartments" in which water is stored. Some of them are regular way stations in the hydrologic cycle, but in the case of groundwater at least, the compartment is just that—a storage area from which it is conceivable that water might not be moved for millions of years.

The vast majority of water on Earth is indeed stored away, deep beneath the planet's surface in the form of groundwater in the lithosphere. This accounts for a staggering 94.7% of Earth's water. (For figures on the mass of this and other components in the water supply, see Hydrologic Cycles.) Much of the remainder is made up of the oceans, which account for 5.2% of the water on Earth, while glaciers and other forms of permanent and semipermanent ice make up 0.065%.

THE LAST 0.035%. We have now identified 99.965% of all water, yet we have not even approached any of the forms of water with which most of us typically come into contact. Of the remaining 0.035%, shallow groundwater, the source of most local water supplies, makes up the



Scanning electron micrograph of the stomata, or pores, on the underside of an apple tree leaf. Leaf pores pull in carbon dioxide for photosynthesis. *(© Scimat/Photo Researchers. Reproduced by permission.)*

bulk, 0.30% of the total. Next are the inland surface waters. All of them combined, including such vast deposits as the Great Lakes and the Caspian Sea as well as the Mississippi-Missouri, Amazon, and Nile river systems—account for just 0.03% of Earth's water.

Now we are left with only 0.02% of the total, which is the proportion occupied by moisture in the atmosphere: clouds, mist, and fog as well as rain, sleet, snow, and hail. While it may seem astounding that atmospheric moisture is such a small portion of the total, this fact says more about the vast amounts of water on Earth than it does about the small amount in the atmosphere. That "small" amount, after all, weighs 1.433×10^{13} tons (1.3×10^{13} tonnes), or 28,659,540,000,000,000 lb.

Water Turnover

The smaller the compartment of water, the greater the amount of turnover—that is, the exchange of "new" water for "old"—and the shorter the turnover time. Groundwater may stay put in aquifers, underground rock formations, for millions of years; on the other hand, atmospheric water experiences an enormous amount of turnover in just a year's time.

The atmosphere receives vast inputs of evaporation from the oceans as well as evapotranspiration from terrestrial ecosystems, or land-based communities of organisms. In the course of the year, the water in the atmosphere turns over about 34 times. Thus, the inputs of evaporation and transpiration are balanced almost perfectly by outputs of precipitation, which return more than 75% of atmospheric moisture to the oceans. The remainder falls on the land, where it contributes to brooks, streams, and rivers. The land receives 67% more water as precipitation than it loses through evaporation. The difference is made up by runoff to the oceans, primarily through rivers and in much smaller portions by subterranean channels.

How Does the Water Move?

Clearly, water is moving through our atmosphere, but *how?* The answer is through gradients, or differences, of energy. When you hold a stone over the side of a cliff, preparing to drop it, the stone possesses a large quantity of gravitational potential energy. This potential energy is a function of the large gradient between the position of the stone and that of the ground.

In the same way, rivers and streams are driven by the gravitational potential that exists by

virtue of the gradient from their source to the place where they empty into a lake or ocean. By definition, water flows downhill, and therefore the source of the river must be at a higher elevation than its delta, or the place where it discharges.

This matter of elevation is reflected in the confusing names for the two kingdoms that united in about 3100 B.C. to form Egypt: Upper Egypt was actually to the south of Lower Egypt. The names reflect the importance of the Nile, which flowed from the higher elevations of Upper Egypt into the fertile lowlands of Lower Egypt, home of Egyptian civilization's greatest farmlands.

EVAPORATION. Evaporation likewise is driven by energy gradients; in this case, however, the energy is not gravitational but electromagnetic. Specifically, it is the energy from the Sun, which we experience in the form of light and heat. (See Sun, Moon, and Earth for more about the Sun's energy.) As surfaces on Earth absorb solar electromagnetic energy, it increases their heat content and provides a source of energy to drive evaporation.

The second law of thermodynamics, discussed in Energy and Earth, tells us that the flow of heat is always from a high-temperature reservoir or area to a low-temperature one. Thus, if you hold a snowball in your hand, you may think that the snowball is cooling your hand, but, in fact, the opposite is happening: heat is passing from your hand into the snowball and warming it. As this happens, your hand loses heat, which you perceive as cold, though no coldness has been transferred—only heat.

In the same way, the energy difference between a heated surface and the atmosphere, manifested as a difference in temperature, makes it possible for water to be vaporized and transported into the air. Though the water has risen rather than fallen, its rise is brought about by the same principle that makes it possible for objects to fall from a great height, that is, a difference in potential. Thus it can be said that in evaporating, water "falls" from an area of high heat and high energy to one of low heat and low energy.

REAL-LIFE APPLICATIONS

Transpiration

When it comes to putting moisture into the atmosphere, transpiration is at least as important as evaporation. In fact, it puts more water into the air than evaporation does: any large area of vegetation tends to evaporate much larger quantities of moisture than an equivalent nonfoliated region, such as the surface of a lake or moist soil. Physically, however, the process of transpiration is the same as that of evaporation.

The only difference is that in the case of transpiration, the source of the evaporation is a biological one—leaves, for instance, as well as skin or lungs. From an environmental standpoint, the most important kind of transpiration is that which occurs through leaves. The loss of water from foliage puts an enormous amount of moisture into the atmosphere, and for this reason, areas where foliage appears in high concentration (i.e., forests) are vital to the cycling of water through the atmosphere.

Plants lose their water through moist membranes of a tissue known as *s*pongy mesophyll, found in the tiny cavities that lie beneath the microscopic leaf pores called stomata. Stomata remain open most of the time, but when they need to be closed, guard cells around their borders push them shut. Because plants depend on them to "breathe" by pulling in carbon dioxide (see Carbon Cycle), however, they keep their stomata open—just as a human's pores must remain open, or the person would die of suffocation.

Because stomata are exposed in order to receive carbon dioxide for the plant's photosynthesis, this also means that the stomata are open to allow the loss of moisture to the atmosphere. It can be said, then, that transpiration—vital as it is to the functioning of our atmosphere—is actually an unavoidable consequence of photosynthesis, an unrelated process.

TRANSPIRATION AND ANIMALS. As we have suggested, transpiration in animals (including humans) takes place for much the same reason as it does with plants, as a by-product of breathing. Animals have to keep their moist respiratory surfaces, such as the lungs, open to the atmosphere. We may not think of our own breathing as transferring moisture to the air, but with just a little consideration of the subject it becomes clear that this is the case. The presence of moisture in our lungs can be proved simply by breathing on a piece of glass and observing the misty cloud that lingers there.

On the one hand, transpiration can cause animals to become dehydrated, but it also can be important in cooling down their bodies. When human bodies become overheated, they produce perspiration, which cools the surface of the skin somewhat. If the air around us is too humid, however, it already is saturated with water, and the perspiration has no place to evaporate. Therefore, instead of continuing to cool our bodies, the perspiration simply forms a sticky film on our skin. Assuming that the air is capable of absorbing more moisture, however, the sweat will evaporate, cooling our bodies considerably.

HEAT, COLD, AND EVAPOTRANSPIRATION

The preceding discussion brings up several more points about the relationship between heat and evapotranspiration. First of all, everything that is living has some degree of heat; if it did not, it would be at a temperature known as absolute zero, or 0K (–459.67°F or –273.15°C), which is impossible to reach. Therefore, even in Greenland there is a small amount of molecular motion in plant tissues, even when they appear to be completely frozen.

Naturally, however, there is very little evapotranspiration when temperatures are extremely cold, which is the reason why it can sometimes be "too cold to snow": temperatures are too low for sufficient moisture to be moved to the atmosphere. Nonetheless, there still can be some physical evaporation as the result of the direct vaporization of solid water, a process called sublimation.

HOT, DRY SUMMERS. At the height of summer, when air temperatures are warm and the trees are fully foliated (i.e., covered in leaves), a high rate of transpiration occurs. So much water is pumped into the atmosphere through foliage that the rate of evapotranspiration typically exceeds the input of water to the local environment through rainfall. The result is that soil becomes dry, some streams cease to flow, and by late summer, in extremely warm temperate areas such as the southern United States, there is a great threat of drought and related problems, such as forest fires.

Once the trees drop their leaves in the autumn, transpiration rates decline greatly. This makes it possible for the parched soil to become recharged by rainfall and for streams to flow again. Such is the case in a temperate region, which by definition is one that has the four seasons to which most people in the United States (outside Hawaii, Alaska, and extreme southern Florida and Texas) are accustomed. In a tropical region, by contrast, there is a "dry season," in which transpiration takes place, and a "rainy season," in which moisture from the atmosphere inundates the solid earth. This rainy season may be so intense that it produces floods.

CLOUDS

So far, we have talked mostly about the means by which water moves from the solid earth into the atmosphere. Now let us consider what happens when it gets there, at which point—assuming there is sufficient moisture—it will coalesce to form a cloud. Though most people are inclined to romanticize clouds, seeing in them shapes and colors and sometimes even reflections of their own moods, clouds are nothing more than atmospheric moisture that has condensed to form tiny droplets of water or crystals of ice.

Heated, moist air that rises from the ground is much more dense than the air that lies above it, but as it rises, it expands and becomes less dense. This expansion cools the air, so that the water vapor condenses into tiny droplets. As a result, a cloud forms, and the relative intensity of the energy gradients that brought about the formation of the cloud creates different shapes.

For example, if there is a vigorous uplift of air, resulting from sharp differences in temperature and pressure between the ground and the atmosphere, the resulting clouds will have a tall, stacked appearance. On the other hand, clouds formed by the gentle uplift of air currents have a flat, cottony appearance. Thus, the shapes of the clouds themselves, as well as the ways in which they change, assist meteorologists in predicting the weather.

CLOUD CLASSIFICATIONS

Thanks to a system developed in 1803 by the English pharmacist and amateur naturalist Luke Howard (1772–1864), it is possible to classify clouds according to three basic shapes. These shapes are known by the Latin names *cumulus* (piled heaps and puffs), *cirrus* (curly, fibrous shapes), and *stratus* (stretched and layered).

Howard combined these names with adjectival terms, such as *alto* ("high") and *nimbus* ("rain"), to describe variations on the three basic cloud types. Today, the International Cloud Classification used by meteorologists worldwide applies Howard's system to the identification of ten basic cloud types, or genera. They are divided into three high-altitude genera, two midlevel ones, three low-level genera, and two varieties of rain cloud.

HIGH-LEVEL CLOUDS. The three genera of high-level clouds appear at a range between 16,500 ft. and 45,000 ft. (5,032–13,725 m), though they usually form in a belt between 20,000 ft. and 25,000 ft. (6,000–7,500 m). All are cirrus clouds, of which the highest are pure cirrus, made of ice crystals.

Then there are cirrocumulus, the least common variety of cloud. Composed of either supercooled water droplets (i.e., water that continues to exist in liquid form even though the temperature has dropped below the freezing point) or ice crystals, these are small and white or pale gray, with a rippled appearance like oatmeal. Finally, cirrostratus clouds—which, like pure cirrus clouds, are made of ice crystals—often form a halo around the Sun or Moon in the wintertime.

MIDLEVEL CLOUDS. The two genera of midlevel clouds, which appear at 6,500-23,000 ft. (2,000–7,000 m), are named with the prefix "alto." Altostratus clouds are usually a uniform bluish or gray sheet covering large portions of the sky and either completely or nearly obscure the Sun and Moon. These complex clouds are composed of layers, with ice crystals at the top, ice and snow in the middle, and water droplets in the lower layers.

Altocumulus are oval-shaped, dense, fluffy balls that may appear either as singular units or as closely bunched groups. When sunlight or moonlight shines through these clouds, the light often is perceived from the ground in the form of rays.

LOW-LEVEL CLOUDS. There are three genera in the low level, which extends from the surface to 6,500 ft. (2,000 m). Pure stratus clouds, which are generally the lowest, blanket the sky and typically appear gray. They are formed when a large mass of air rises slowly or when cool air moves in over an area close to ground level. Stratus clouds may produce mist or drizzle, or, when they form at ground level, they may appear as fog.

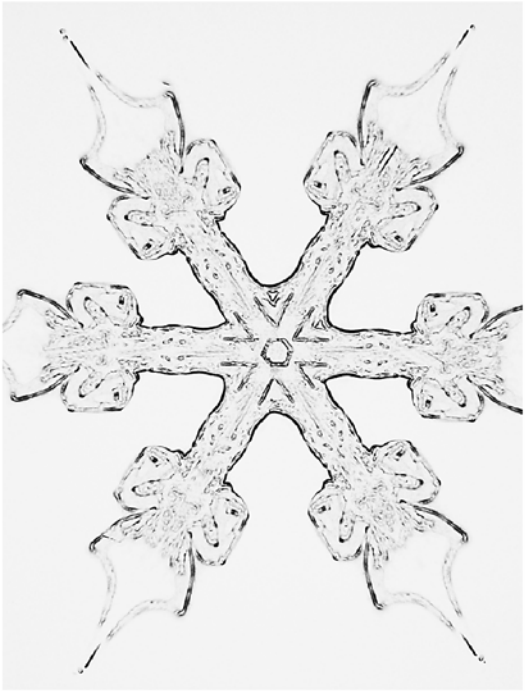


WHEN MOISTURE COALESCES IN THE ATMOSPHERE, IT FORMS A CLOUD. ALTOCUMULUS CLOUDS, WHICH LOOK LIKE OVAL-SHAPED, DENSE, PUFFY BALLS, ARE MIDLEVEL CLOUDS. *(© Mark A. Schneider/Photo Researchers. Reproduced by permission.)*

Pure cumulus clouds are flat on the base and vertically thick, with a puffy appearance on top. This puffiness is the result of updrafts. Occurring primarily in warm weather, cumulus clouds are made of water droplets and look brilliant white because of the sunlight's reflection off the droplets. Last, stratocumulus clouds are large, grayish, and puffy, often looking like dark rolls.

RAIN CLOUDS. Stratocumulus clouds can transform into nimbostratus clouds, while cumulus can develop into cumulonimbus clouds. These two—nimbostratus and cumulonimbus—are the last of the ten varieties of cloud, designated not by altitude but by the fact that they give rise to precipitation. (Note that the light, airy variety known as *cirrus* never portends rain.)

Nimbostratus usually appear at midlevel altitudes. Made of water droplets that produce either rain or snow, they are thick, dark, and gray.



MICROGRAPH OF A SNOWFLAKE. SNOWFLAKES ARE FORMED BY THE BONDING OF SOLID ICE CRYSTALS INSIDE A CLOUD. *(© Kent Wood/Photo Researchers. Reproduced by permission.)*

Sometimes they are seen with virga, which are skirts of rain trailing down their sides.

Cumulonimbus, or thunderstorm, clouds arise from cumulus clouds that have reached a great height. At a certain height, the cloud flattens out, and powerful updrafts and downdrafts create a great deal of unrest inside the cloud, which contains all phases of water: gas, liquid, and solid. These clouds can cause violent storms.

RAIN, SNOW, HAIL, AND SLEET

Eventually, the amount of moisture in the cloud becomes so great that it has to fall earthward in the form of precipitation—usually rain, snow, hail, or sleet. These types of precipitation are distinguished by the form they take: liquid in the first case, lightly frozen particles in the second case, and hard, frozen nuggets in the latter two cases.

Liquid precipitation includes drizzle and raindrops, which are distinguished from each other on the basis of size. Raindrops have a radius of about 0.04 in. (1 mm), while drops of drizzle are about one-tenth that size. Note the use of the term radius, implying a sphere. Drops of liquid precipitation are spherical, and though a teardrop shape is popularly associated with raindrops, they assume that shape only when they are falling.

Snowflakes are formed by the aggregation, or physical bonding, of solid ice crystals inside a cloud, while hailstones are made of a combination of supercooled water droplets and pellets of ice. Not only are they more dense than snowflakes, but they are also more spherical. Similar to hail is sleet, pellets of pure ice that usually are much smaller than hail.

FORMING PRECIPITATION. The type of precipitation formed depends on the warmth of the cloud from which it comes. "Warm" clouds are those whose temperatures are above freezing—32°F (0°C)—and "cold" clouds are those that are at least partially below freezing temperature. These temperature values are themselves a function of altitude, since temperature in the lower atmosphere (where all precipitation occurs) decreases by about 5.32°F for every mile (6°C per kilometer) of altitude gained.

As we have suggested earlier, humidity relates to the ability of air to evaporate, and, therefore, when the air has all the water it can hold, it is said to have a relative humidity of 100%. The cooler air is, the less moisture is required for it to become saturated. Once saturation occurs, moisture molecules form around cloud condensation nuclei, such as nitrates or extremely fine particles of sea salt that have managed to evaporate.

Cold clouds form around ice crystals. Before freezing, the water in these clouds may be supercooled,. Ice nuclei are much more rare than cloud condensation nuclei and are less well understood by meteorologists.

MIXED CLOUDS. Clouds that contain both liquid water and ice are called mixed clouds. Supercooled water will freeze when it strikes an ice crystal, and if it freezes immediately, it forms what is known as opaque or rime ice. If it freezes slowly, the result is called clear ice. Eventually the ice forms a thick coating, which is the origin of hail.

Not all mixed clouds produce frozen precipitation, however. Thunderstorms, involving electric charges imparted to precipitation particles, which leads to the eventual discharge of lightning, are also the products of mixed clouds. (For more about storms and precipitation, see Weather and Climate.)

KEY TERMS

AQUIFER: An underground rock formation in which groundwater is stored.

ATMOSPHERE: In general, an atmosphere is a blanket of gases surrounding a planet. Unless otherwise identified, however, the term refers to the atmosphere of Earth, which consists of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon (0.07%).

BIOSPHERE: A combination of all living things on Earth—plants, mammals, birds, amphibians, reptiles, aquatic life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

ECOSYSTEM: A community of interdependent organisms along with the inorganic components of their environment.

EVAPORATION: The process whereby liquid water is converted into a gaseous state and transported to the atmosphere. When discussing the atmosphere and precipitation, usually evaporation is distinguished from transpiration. In this context, evaporation refers solely to the transfer of water from nonliving sources, such as the soil or the surface of a lake.

EVAPOTRANSPIRATION: The loss of water to the atmosphere via the combined (and related) processes of evaporation and transpiration.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

GROUNDWATER: Underground water resources that occupy the pores in bedrock.

HYDROLOGIC CYCLE: The continuous circulation of water throughout Earth and between various earth systems.

HYDROLOGY: The study of the hydrosphere, including the distribution of water on Earth, its circulation through the hydrologic cycle, the physical and chemical properties of water, and the interaction between the hydrosphere and other earth systems.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

METEOROLOGY: The study of the atmosphere, weather, and weather prediction.

POTENTIAL: Position in a field, such as a gravitational force field.

POTENTIAL ENERGY: The energy that an object possesses by virtue of its position or its ability to perform work.

PRECIPITATION: When discussing the hydrologic cycle or meteorology, precipitation refers to the water, in liquid or solid form, that falls to the ground when the atmosphere has become saturated with moisture. In the context of chemistry, precipitation refers to the formation of a solid from a liquid.

SUPERCOOLED: A term for water that continues to exist in liquid form even though its temperature has dropped below the freezing point.

KEY TERMS CONTINUED

SYSTEM: Any set of interactions that can be set apart mentally from the rest of the universe for the purposes of study, observation, and measurement.

TRANSPIRATION: The process whereby moisture is transferred from living organisms to the atmosphere. A major portion of environmental moisture for precipitation comes from plants, which lose water through their stomata, small openings on the undersides of leaves.

WATERSHED: An area of terrain from which water flows into a stream, river, lake, or other large body.

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WEATHER

CONCEPT

Though people are quite accustomed to experiencing weather—sunshine and rain, wind and storms, hot and cold, fair days and foul—most have little idea how weather originates or even really what weather is. In fact, it is a condition of the atmosphere produced by one or more of six factors: air temperature, air pressure, humidity in the air, the density and variety of cloud cover, the amount and type of precipitation, and the speed and direction of the wind. Those six variables can produce the sunny, beautiful days that everyone treasures, or they can conspire to create the sort of rainy, windy, and cold day that some people despise and others (especially creative types, who do not have to be out in the elements) adore. The variables of weather also can align to manifest in the form of brutal storms, including hurricanes and tornadoes. Yet as complex as weather is, its behavior can still be forecast—with at least some accuracy—and sometimes even manipulated.

HOW IT WORKS

Introduction to Weather

Weather and climate are not the same thing: weather is the condition of the atmosphere at any given time and place, while climate is the pattern of weather conditions in a particular region over an extended period. We do not speak therefore of "forecasting climate," though it is possible, on the basis of long-term climate patterns, to make some predictions concerning future climatic trends. (Climate is discussed in a separate essay.)

Nevertheless, the type of atmospheric prediction that applies much more to our daily lives is weather forecasting. The latter is the work of meteorologists, or scientists involved in studying the atmosphere and weather and in making weather predictions. In the 1970s most local television news programs still included a "weatherman" on their lineup. This was a television personality, much like the anchors and the specialists in sports or other topics, whose job it was to report the weather. During the late 1970s and early 1980s, however, most stations and networks changed their designation of weatherman to that of meteorologist.

In part this change had to do with gender politics, since the title weatherman seemed sexist but weatherwoman or weatherperson sounded a bit absurd. On the other hand, it also was made in recognition of the work that weather forecasters perform: unlike ordinary reporters, they are not so much journalists as they are scientists. (Though a nice smile, charming personality, and good looks never hurt any TV meteorologist!) And while a meteorologist, like every member of the TV news team, reports what has happened—for instance, a record snowfall—his or her job also is concerned heavily with explaining what *will* happen.

SIX FACTORS. As we have noted, weather is determined by six factors, all of which involve the atmosphere, and several of which also relate to water in the atmosphere. These factors are as follows:

- Air temperature
- Air pressure
- Wind
- Humidity

- Cloud cover
- Precipitation

The role of air temperature in weather is fairly obvious, since that is one factor of which we are used to taking note on a regular basis. Air pressure, though much less familiar to most of us, has a powerful influence on air currents, and air pressure is linked closely with wind. Likewise, there are clear linkages among humidity (moisture in the air), the amount and type of cloud cover (formed, of course, from moisture in the air), and the amount and type of precipitation, which begins to fall when the clouds are saturated with moisture.

What Makes the Weather?

So much for the factors involved in weather, which go into making the weather we experience at a given time. But if we want to search for the ultimate causes behind the weather, we have to look toward larger phenomena: the Sun and Earth as well as Earth's surface and atmosphere and the interactions among all of these factors.

At the heart of weather is the Sun and the energy it transmits to Earth. As discussed in Energy and Earth, the Sun sends out vast quantities of energy, only a small portion of which comes anywhere near Earth—and a much smaller portion reaches the surface of the planet as usable energy. Yet that "tiny" amount, which is the vast majority of the energy available to Earth in any form, is enough to light and warm the planet and to drive a variety of processes in the biosphere and atmosphere.

MOVING WATER THROUGH THE ATMOSPHERE. The Sun's most direct and obvious influence on weather is its impact on temperature, but this is only one aspect of a larger and more complex picture. As discussed in the essay Evapotranspiration and Precipitation, differences in temperature—a result, primarily, of the Sun's heat—make possible the conditions for both evaporation and transpiration, or the loss of moisture from living organisms to the atmosphere.

The amount of water that evaporates into the atmosphere in a given area is its humidity, which exerts a powerful impact on the human experience of weather. As most people who have traveled widely will attest, high temperatures in a dry climate, such as that of the American Southwest, are far easier to endure than equally high temperatures (or even lower ones) in Florida or other parts of the Deep South, a much more humid region.

As water moves from Earth's surface into the atmosphere through evapotranspiration (a combination of evaporation and the related process of transpiration), the air through which it passes becomes increasingly cooler. Eventually, the vaporized water comes to an altitude at which the air around it is cold enough to cause condensation—that is, the formation of a liquid. When enough vapor has condensed into tiny droplets of water, or tiny ice crystals, the result is the formation of clouds.

Clouds, discussed in detail within the context of Evapotranspiration and Precipitation, are integral to the formation of weather patterns, which is why TV meteorologists almost always show their audiences satellite maps illustrating cloud movements. Not only do clouds reflect sunlight into space, meaning that a sufficient accumulation of cloud cover will bring about a decrease in temperature, but clouds also manufacture precipitation. Forms of precipitation include rain in all its variations, from a fine mist to a downpour, as well as snow, sleet, and hail.

Air Pressure and Wind

We have seen how the Sun affects the movement of water through the atmosphere, thus driving three of the six key weather factors we named earlier: humidity, cloud cover, and precipitation. In addition to its effect on these factors and on temperature itself, the Sun and its energy are also behind the other two important factors—air pressure and the movement of air through the atmosphere, that is, winds.

Because it does not change as frequently or as dramatically as temperature (fortunately!), air pressure is something of which we are hardly aware. But if a person accustomed to the sea-level air pressure of a place such as New York City suddenly had to travel to a high-altitude locale such as Denver, Colorado, he or she immediately would become aware of the difficulty in breathing and the other changes that attend a change in pressure.

For instance, the higher the altitude (and, hence, the lower the air pressure), the lower the temperature at which water boils. For this reason, cake mixes and similar products have special instructions for kitchens at high altitudes. Taken

to an extreme, this means that with absolutely no pressure, liquid could boil—that is, turn into a vapor—at extremely low temperatures. This is one of the reasons, along with lack of oxygen and the presence of harmful rays, that an astronaut wears a protective suit; without it, the pressureless environment of space would cause a person's blood to boil!

In the English system, normal atmospheric pressure at sea level is 14.7 lb. per sq. in., or 1.013×10^5 pascals (Pa) in the metric or SI (Scientific International) system. This amount of pressure constitutes a unit in its own right, an atmosphere (atm). Atmospheric pressure, however, usually is measured in terms of the bar, an SI unit equal to 10^5 Pa. Thus, 1 atm = 1.013 bars. Meteorologists often use the millibar (mb), which, as its name implies, is equal to 0.001 bars—roughly 1/1,000 of ordinary air pressure at sea level.

WIND: FROM HIGH PRESSURE TO LOW. Heat from the Sun does not fall evenly on all places on Earth. Aside from the obvious fact that it makes a limited impact on polar regions, there are the differences in color and texture between various areas, even in the most tropical latitudes—that is, those closest to the direct path of sunlight. For example, soil, since it is almost always darker than water, tends to attract more sunlight than bodies of water do.

When an area is heated, the air above it heats up as well, and this makes that region of air less dense. As a result, the air rises, a phenomenon known as convection. Convection currents also carry other masses of air downward from the upper atmosphere toward Earth's surface. In regions where warm air moves upward, the atmospheric pressure tends to be low, whereas downward air movements are associated with higher atmospheric pressures.

These higher or lower atmospheric pressures can be measured by a barometer, an instrument that registers pressure just as a thermometer measures temperature. The fact that there are differences in pressure between areas brings about wind, which is the movement of air from a region of high pressure to one of lower pressure. (Later in this essay, we discuss a way to "create" wind and thus test this statement.)

Other Influences on Weather

We have focused primarily on the influence that the Sun and its energy exerts on weather, but it should be noted that certain aspects of Earth itself determine weather patterns. Among these factors, as noted earlier, are color and texture, whereby certain places on the planet are more apt to receive the Sun's energy than others.

Also important is Earth's position in space. First of all, there is the tilt of its axis relative to the plane of its rotation around the Sun, which accounts for the seasons. In addition, the planet follows an elliptical, or oval-shaped, orbital pattern around the Sun, which means that there are certain times when the planet is closer to the Sun and its energy than at others.

Earth's rotation brings about complicated patterns of movement on the part of air masses heated at the equator. If the planet were not rotating, these masses of air would simply move from the equator toward the poles, where they would be cooled. Because the planet is rotating, however, the movement of global winds is much more complex and is characterized by circular patterns known as *cells*.

In addition to these factors that relate to the planet's movement in space, there is also the matter of irregularities on Earth's surface. An example of this is the effect mountains can have on cloud movements, creating a perpetually rainy climate on one side and a dry "rain shadow" on the other. Rain shadows are discussed in the essay on Mountains.

REAL-LIFE APPLICATIONS

Creating Wind

Earlier we discussed the fact that wind results from differences in pressure. This is a statement you can test for yourself—and perhaps you already have, without knowing it. Suppose you are in a room where the heat is on too high and there is no way to adjust the thermostat. Outside the air is cold, so you open a window, hoping to cool down the room. Does it do the trick? Not likely. But if you open the door leading from the room to the hallway, a nice cool breeze will blow through. You have, in effect, created wind or at least manipulated the conditions to make wind possible.

With the door closed, the room constitutes an area of high pressure in comparison with the area outside the window. Once the window alone

is opened, it is theoretically possible for air to flow into the room, but that does not mean the air actually will flow. The reason is that fluids such as air—whether in a room or in the sky—tend to move from areas of high pressure to areas of low pressure. Because the room is of relatively high pressure compared with the outside, there is no reason for the air to move into the room.

Furthermore, in line with the second law of thermodynamics (see Energy and Earth), the flow of heat always will be from an area of relatively high temperature to one of relatively low temperature. Therefore, if there is going to be any air movement in this situation, it will have to be movement of hot air *out* of the room rather than cool air *into* the room. (Even an air conditioner works by taking out the heat, not by bringing in "cold"—even though we may perceive it otherwise.)

In the case of the overheated room, there is only one way to solve the problem: by opening the door into the hallway, or whatever else lies outside the door. As soon as the door is opened, the relatively high-pressure air of the room flows into the relatively low-pressure area of the hallway, just as the laws of physics say it should. This is exactly the same principle whereby wind blows from high-pressure regions into low pressure ones. By setting up a cross-draft, in effect, we have "created" wind.

Thunderstorms and Worse

Wind and clouds combined with rain (discussed, like clouds, in Evapotranspiration and Precipitation) and a few other factors create a thunderstorm. Those other factors, of course, are lightning and that key difference between an ordinary storm and a thunderstorm: thunder.

Inside a thunderstorm are updrafts and downdrafts of air, which bring about a buildup of static electric charges within the thunderstorm clouds. Over time, there is a large buildup of separate electric charges inside the cloud, with positive charges near the top and negative charges in the middle. This separation of charges creates huge voltage differences, which require something to equalize them: a bolt of lightning, which suddenly passes between the areas of differing charge.

Lightning produces a spark, which heats the air in an instant to more than 54,000°F (30,000°C). As a result, the molecules of air and moisture in the cloud experience an extremely sudden expansion, and this expansion is accompanied by a release of energy. The energy in this situation takes the form of sound, which we experience as thunder.

ANATOMY OF A THUNDERSTORM. Let us go back now to the point when the thunderstorm came into being. First solar energy, or some other influence, such as the presence of a mountain range, causes water to enter the atmosphere as vapor. As this air rises, it expands and cools, eventually condensing and coalescing to form a cloud. The cloud thus formed is a cumulus cloud, which may appear as the puffy, benign cloud of a clear summer's day or may turn into a cumulonimbus—a thunderstorm—cloud.

On its way to becoming a thunder cloud, a cumulus undergoes a transformation into a convective cloud, or one formed by convection. It may never become a thunder cloud at all, assuming that vertical movement stops, in which case fair weather prevails. But if the atmosphere is unstable, meaning that the air temperature drops rapidly with altitude, packets of air that begin rising and cooling inevitably will be warmer than the air around them. The rising air packet is like a balloon, weighing less per unit of volume than the surrounding area, and thus it continues to rise.

As we have noted, in order to evaporate, water needs to receive a certain infusion of energy, or heat, from the Sun. Once it condenses and forms a cloud, it releases that heat, warming the cloud and causing it to rise still higher. As long as these updrafts can support the cloud, it continues to grow and to rise, until, in the case of a thunderstorm, it reaches very great atmospheric heights—about 40,000 ft. (12 km) above the surface. In the course of rising and growing, large raindrops and hailstones can form.

TWO TYPES OF THUNDERSTORM. Over western Florida and other areas around the Gulf of Mexico, thunderstorms grow as we have described, with cumulus clouds rising and cooling. These are called air-mass storms. Once the cloud reaches a certain point of moisture saturation, rain begins to fall from the upper part of the cloud, producing precipitation and with it downdrafts. Because the downdraft in such a situation is usually stronger than the updraft, the cloud is likely to dissipate before the

thunderstorm has caused much damage. Certainly there will be rain showers, thunder, and lightning, but the storm is unlikely to produce extreme wind damage or hail.

On the other hand, parts of the central and eastern United States are prone to what are called frontal thunderstorms, and these storms are much more severe. They typically form just ahead of a cold air mass, or cold front. The cold air, much more dense than the warm, humid, and unstable air of the cloud system, pushes the clouds ahead of it, which rise and form convective clouds. Eventually, these clouds produce rain, which causes downdrafts. But instead of dissipating the storm's impact (as in the case of the air-mass storm), the downdrafts only increase its intensity.

In a frontal thunderstorm, strong downdrafts hit the ground, spreading out and sending more warm humid air rising into the storm. This gives the storm clouds more latent heat, increasing the updrafts, which in turn gives more speed to the wind and improves the chances of heavy rain or even hail. The latter can appear even in summertime or in warm climates, since the cloud forms at a great height.

When ice crystals form in the cloud, the updrafts and downdrafts circulate them back and forth, and as this happens, the crystals pick up more and more moisture. Eventually, tiny ice crystals gather rainwater around them, until they have become hailstones. Depending on the conditions of the storm, hailstones can become extremely large—as big as 5.5 in. (14 cm) in diameter.



AS CLOUDS RISE AND GROW, ICE CRYSTALS FORM AND GATHER RAINWATER AROUND THEM UNTIL THEY BECOME HAILSTONES. DEPENDING ON THE CONDITIONS OF THE STORM, HAILSTONES CAN GROW EXTREMELY LARGE—MORE THAN TWICE THE SIZE OF THE GOLF BALL–SIZE ONES SHOWN HERE. *(© Gary Meszaros/Photo Researchers. Reproduced by permission.)*

TORNADOES

Some forms of weather make thunderstorms seem minor by comparison. Among these are tornadoes, a rapidly spinning column of air formed in a severe thunderstorm. The vortex, or rotating center, of the column, forms inside the storm cloud and begins to grow downward until it touches Earth's surface. The United States is particularly prone to tornadoes, owing to specific factors of its location and its larger climate patterns. (See Climate for more about the distinction between weather and climate.)

The type of severe frontal thunderstorm that can produce a tornado typically is associated with an extremely unstable atmosphere and with moving systems of low pressure, which bring masses of cold air into contact with warmer, more humid air masses. It so happens that such storms occur frequently across a wide swath of North America, from the plains states to the eastern seaboard (i.e., more or less from Kansas to North Carolina) during a period from about June to October each year.

As updrafts in a severe thunderstorm cloud become stronger, they pull more air into the base of the cloud to replace the rising air. As the air from the surface moves into a smaller area, it begins to rotate faster, owing to what physicists call the conservation of angular momentum. The latter can be illustrated by the example of an ice skater who, while spinning with her arms outstretched, pulls her arms inward. As she does so, the speed of her rotation increases. The same happens with rotating air as it moves from the large space of the ground to the smaller space of the cloud.

Thus, a funnel cloud is produced and grows, and if it becomes large enough, it may touch

ground—with devastating results. Within the vortex of a tornado, which is typically about 328 ft. (100 m) in diameter, wind speeds may be greater than 220 MPH (100 m/s). The tornado itself travels at speeds of 10–30 MPH (15–45 km/h), making a sound like a freight train or a jet engine and wreaking havoc along a path as long as 200 mi. (321 km). Nothing can stand in the way of a tornado with enough force: buildings shatter, roofs and whole houses take to the air, and pieces of straw can be blown through solid wood.

TORNADO ALLEY. No country in the world is more prone to tornado activity than the United States, a large portion of which is known as "Tornado Alley." The latter area has no specific boundaries, though it is more or less contiguous with the wide Kansas-to-Carolina swath mentioned earlier. Some authorities describe Tornado Alley as including northern Texas, Oklahoma, Kansas, and southern Nebraska. However, the American Meteorological Society's *Glossary of Weather and Climate* defines Tornado Alley as "The area of the United States in which tornadoes are most frequent. It encompasses the great lowland areas of the Mississippi, the Ohio, and lower Missouri River valleys. Although no state is entirely free of tornadoes, they are most frequent in the plains area between the Rocky Mountains and the Appalachians."

It is no accident that a wide, flat region, over which heavy winds can blow from numerous directions—including winds off of the Gulf of Mexico and Atlantic Ocean—would be home to such enormous tornado activity. Tornado Alley, or parts of it, has seen numerous extraordinary weather events in which not one or two tornadoes struck, but many dozens—a phenomenon known as a tornado outbreak, or a super outbreak.

The worst super outbreak in recent memory occurred on April 3–4, 1974, when 148 rampaged through 14 states. It began on the morning of the 3rd, when a low-pressure system moved over central Kansas, spreading a cold front as far south as Texas. Meanwhile, a warm front clung to the lower Ohio River Valley, and various unstable patterns covered the South. Into this motley mix came strong winds, which soon took hold over much of the eastern United States. By afternoon, thunderstorms began raging over much of the Midwest and South, including the Ohio and Tennessee River valleys.

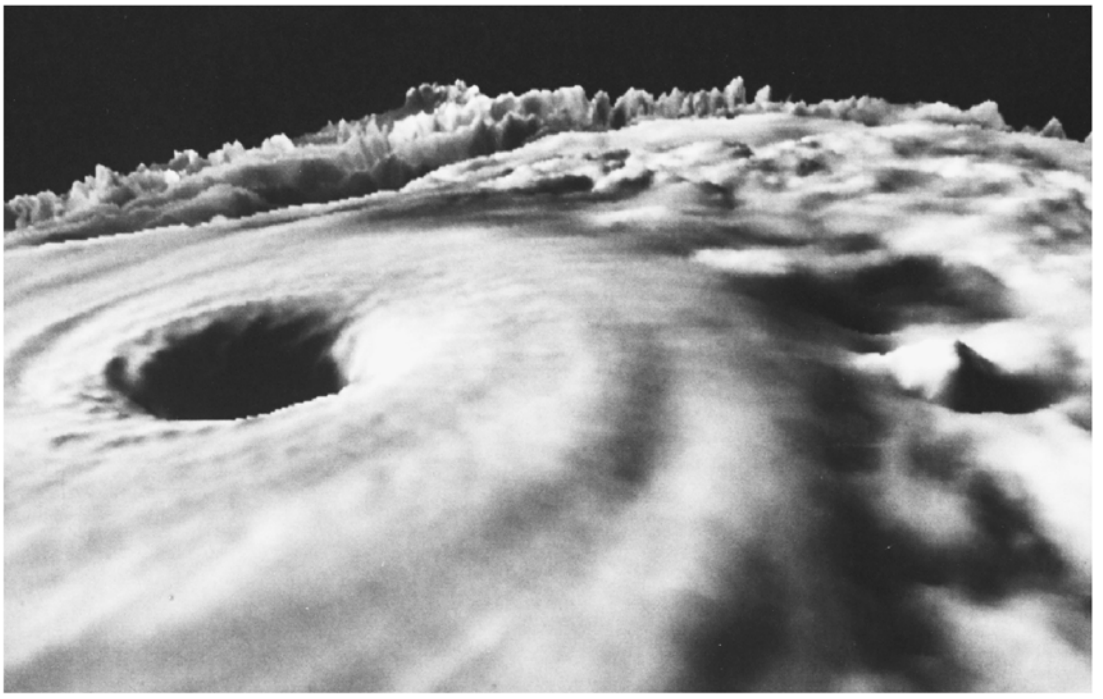
The result was a series of nearly 150 tornadoes, including 48 that were classified as F4 or F5, the highest levels on the Fujita-Pearson scale used to rate the intensity or tornadoes. Some other significant tornado events since that time include the Carolina outbreak, which killed 57 people, injured 1,248, and caused $200 million in damage, on March 28, 1984. A year later, on May 31, 1985, an outbreak of 41 tornadoes in Ohio, Pennsylvania, New York, and Ontario killed almost 90 people and caused over $450 million in damage.

CYCLONES

Another form of extreme weather is a cyclone, a general term for what is sometimes called a hurricane or a typhoon. These are vast circulating storm systems characterized by bands of showers, thunderstorms, and winds. They develop over warm tropical oceans, generally as isolated thunderstorms, and turn into monsters. A cyclone may have a diameter as great as 403 mi. (650 km) and be more than 7.5 mi. (12 km) in height.

Near the center of the cyclone, winds may be as high as 110 MPH (50 m/s), yet the very center is an area of complete calm, known as the eye. This is a region of descending air surrounded by the updrafts that characterize the cyclone, making the eye a little funnel of peace in the middle of a terrible storm. If it were possible to stay in the eye of the cyclone as it moves—at speeds comparable to that of a tornado—it is conceivable one could come away unscathed.

THE IMPACT OF CYCLONES. Once the cyclone blows inland and reaches population centers, it can cause massive death and destruction. The southern United States witnessed this with hurricanes such as Hugo, which devastated the Carolinas and nearby regions in 1989. The damage on Puerto Rico alone (one of the places Hugo touched down before moving north) amounted to 12 lives lost, and $2 billion in property. Thanks to evacuation measures and a bit of good fortune (the hurricane missed Charleston, South Carolina), loss of life was minimal on the continental United States, and loss of property was kept to $5 billion. By contrast, Hurricane Andrew, which struck Florida and other parts of the southern United States in August



A GLOBAL NETWORK OF WEATHER SATELLITES MAKES IT POSSIBLE TO IDENTIFY AND TRACK TROPICAL CYCLONES FROM THEIR EARLIEST APPEARANCE AS DISTURBANCES OVER THE OCEAN. A CYCLONE CAN GENERATE WINDS AS HIGH AS 110 MPH (50 M/SEC), YET THE VERY CENTER IS AN AREA OF COMPLETE CALM, KNOWN AS THE EYE. *(U.S. National Aeronautics and Space Administration [NASA].)*

1992, was the costliest natural disaster in U.S. history, with over $25 billion in damage reported.

But the impact of storms in the United States is dwarfed by the destruction of hurricanes and typhoons in third world countries. Bangladesh, for instance, is a country where a population half that of the United States is crammed into an area the size of Wisconsin. (And, it should be noted, a country so poor that the income of the average full-time working man is far less than that of an American teenager working a part-time job.)

In such a situation, the impact of cyclones is bound to be devastating. Though dollar figures of property damage from the country's many cyclones are not available, the human toll is better known. Since 1963, when it was still called East Pakistan, Bangladesh, has seen seven cyclones in which 10,000 or more died. The worst, in 1970, killed half a million. Government estimates of deaths from a cyclone on April 10, 1991, were 150,000, though it is likely that many more died from disease, starvation, and exposure.

Likewise, typhoons in such countries as the Philippines cause massive power outages, flooding, landslides, and destruction of life and property. In part this is because a number of these countries are located in or near tropical zones that are especially susceptible to cyclones, but it is also a matter of preparedness.

RESPONDING TO CYCLONES. In the United States, with its greater material wealth and technological sophistication, it is possible to prepare people for extreme weather in a way that is simply beyond the reach of many less prosperous or powerful nations. It is not so much that Americans are capable of developing structures such as seawalls that can withstand the force of hurricanes, though this certainly helps. The seawall in Charleston, South Carolina, for instance—a massive bulwark of concrete more than 10 ft. (3 m) high—is intended to protect homes in that city's historic Battery when hurricanes produce powerful ocean swells.

Much of the effectiveness of the American response to hurricanes, however, is attributable to the ability to react to circumstances rather than to prevent them. With a large amount of the population possessing electronic communication, it is possible to circulate word quickly regarding the coming deluge. Furthermore, people in the United States are much more mobile



DRY ICE (SOLID CARBON DIOXIDE), SEEN HERE BEING CONVERTED INTO A VAPOR, OFTEN IS USED TO CHANGE SUPERCOOLED WATER IN CLOUDS INTO ICE CRYSTALS IN THE WEATHER MODIFICATION TECHNIQUE CALLED CLOUD SEEDING. *(© M. Meadow/Photo Researchers. Reproduced by permission.)*

than their counterparts in developing countries and can evacuate hurricane regions more easily. Additionally, a wealthier and more powerful government is able to administer relief more quickly and in greater quantities than the leadership of small, poor nations.

Even so, hurricanes and typhoons have a vast impact wherever they strike, and perhaps for this reason a certain mystery and lore have developed around them. Reflective of this fascination is the practice of personalizing hurricanes. Originally, the U.S. National Weather Service gave them women's names, but in response to protests from feminist groups, by the late 1970s it had adopted a practice of using an alphabetic list of alternating male and female first names. The Weather Service draws up new lists each year to name the cyclones of the western Pacific and the Caribbean/Gulf regions.

Forecasting and Controlling Weather

Until the twentieth century, people had little warning when a cyclone was coming. Early in that century, however, the establishment of hurricane-watch services offered the hope of early warning, and by the 1930s ships and weather balloons were used to provide readings on atmospheric conditions that might portend cyclones. In the 1940s airplanes and, later, radar further increased meteorologists' ability to monitor the atmosphere. Today a global network of weather satellites makes it possible to identify and track tropical cyclones from their earliest appearance as disturbances over the remote ocean.

From the time of the Greeks, at least, people have tried to forecast the weather. They attempted to do so with varying degrees of success, using means that included folklore, superstition, old wives' tales, traditional wisdom, instinct, intuition, and even a little bit of science. Sometimes this mixed bag yielded valuable information, such as the old and essentially accurate saying "Red sky at morning, sailors take warning; red sky at night, sailor's delight." Yet without true scientific methods of forecasting, would-be meteorologists were just shooting in the dark—as the sometimes inaccurate results of today's much more scientific forecasting shows.

A turning point came in the twentieth century, with the development of such monitoring systems as the cyclone-monitoring techniques we have mentioned. It says a great deal about just how young meteorology is as a science that one of its two founders as a modern discipline died only in the 1970s. This was Jakob Bjerknes (1897–1975), a Norwegian-born American meteorologist who, in the 1920s, established a network of weather stations with his father, the Norwegian physicist Vilhelm Bjerknes (1862–1951). Vilhelm proposed the idea of air masses, a pivotal concept in meteorology, while Jakob discovered the origin of cyclones.

MODERN WEATHER FORECASTING. Weather forecasting in the United States is the responsibility of the National Weather Service (NWS), which is part of the National Oceanic and Atmospheric Administration (NOAA) within the Department of Commerce. The NWS maintains a vast network of field offices and weather stations as well as nine National Centers for Environmental Prediction, each of which is focused on specific weather-related responsibilities. The complexity of the NWS organizational system hints at the greater

KEY TERMS

ATMOSPHERE: In general, an atmosphere is a blanket of gases surrounding a planet. Unless otherwise identified, however, the term refers to the atmosphere of Earth, which consists of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon (0.07%).

CLIMATE: The pattern of weather conditions in a particular region over an extended period. Compare with *weather.*

CONDENSATION: The formation of a liquid from a vapor, usually as a result of a reduction in temperature.

CONVECTION: Vertical circulation that results from differences in density ultimately brought about by differences in temperature. Convection involves the transfer of heat through the motion of hot fluid (e.g., air) from one place to another.

CONVECTION CURRENT: The flow of material heated by means of convection.

EVAPORATION: The process whereby liquid water is converted into a gaseous state and transported to the atmosphere. When discussing the atmosphere and precipitation, evaporation generally is distinguished from transpiration. In this context, evaporation refers solely to the transfer of water from nonliving sources, such as the soil or the surface of a lake.

EVAPOTRANSPIRATION: The loss of water to the atmosphere via the combined (and related) processes of evaporation and transpiration.

HUMIDITY: The amount of water vapor in the air.

METEOROLOGY: The study of the atmosphere, weather, and weather prediction.

PRECIPITATION: When discussing the hydrologic cycle or meteorology, precipitation refers to the water, in liquid or solid form, that falls to the ground when the atmosphere has become saturated with moisture.

TRANSPIRATION: The process whereby moisture is transferred from living organisms to the atmosphere. A major portion of environmental moisture for precipitation comes from plants, which lose water through their stomata, small openings on the undersides of leaves.

UNSTABLE ATMOSPHERE: A term describing a situation in which air temperature drops rapidly with altitude. As a result, a packet of air continues to move upward owing to the temperature difference between it and the surrounding air.

WEATHER: The condition of the atmosphere at a given time and place. Compare with *climate.*

complexity of weather forecasting itself, which we touch on here in only the most cursory fashion.

A number of useful techniques and forms of technology are available to the modern meteorologist. Perhaps the best known of these is Doppler radar, used to track the movement of storm systems. By detecting the direction and velocity of raindrops or hail, Doppler radar can help the meteorologist determine the direction of winds, and thus predict weather patterns that will follow in the next minutes or hours. But Doppler radar can do more than simply detect a

storm in progress: Doppler technology also aids meteorologists by interpreting wind direction. Other forms of weather-forecasting technology include NEXRAD (Next Generation Radar) and GOES (Geostationary Operational Environmental Satellite).

SOME TYPES OF WEATHER FORECAST. The simplest (and usually least accurate) type of forecast is called a persistent forecast and starts with the assumption that existing patterns will continue into the future. The problem with this notion, of course, is that with the complexity of weather, patterns are always changing. More reliable is the so-called trend method, based on the relationship between the movement of air masses and the larger weather patterns. This is a type of prediction familiar to most of us from weather maps displayed by TV meteorologists.

Similar to the trend method is the analogue method, which uses analogies (hence the name) between current weather maps and similar maps from the past. If a weather map for today closely matches the map of patterns that prevailed on a particular day three years ago, it is possible to make some predictions about the weather now by referring to conditions that developed at that time.

Meteorology may employ statistical probability, and when it comes to long-range forecasting, the mathematics may become considerably more complex. This is illustrated by the fact that chaos theory, one of the most challenging branches of modern mathematics, was the brainchild not of a mathematician but of the American meteorologist Edward Lorenz (1917–). An outgrowth of Lorenz's studies in atmospheric patterns, chaos theory is applied in studying extremely complex systems whose behavior appears random. (On a pop-culture note, chaos theory was the specialization of Ian Malcolm, the mathematician played by Jeff Goldblum in the film, *Jurassic Park.*)

"MAKING" WEATHER. People at the turn of the nineteenth century would have been flabbergasted to know that it would be possible by the twenty-first century to provide a reasonably accurate 24-hour weather forecast. They would have been even more astounded at the idea of a five-day forecast, which is common (though with varying degrees of accuracy) on most local and national weather reports. And, no doubt, they would have been "blown away"—to use a popular weather metaphor—at the concept that modern technology makes it possible even to exert some control over the weather.

Weather modification includes techniques such as cloud-seeding, which originated in the 1940s. By the beginning of the twenty-first century, several other methods of weather modification existed, among them frost prevention, fog and cloud dispersal, hurricane modification, hail suppression, and lighting suppression.

Cloud seeding necessitates the conversion of supercooled water in clouds—that is, water whose temperature has dropped below the freezing point without it actually freezing—into ice crystals. Dry ice (solid carbon dioxide) and silver iodide are the substances most commonly employed for this purpose. The result is, or at least can be, snow clouds. On the other hand, cloud-seeding techniques can be used for fog dispersal, another form of weather modification useful, for instance, in the skies over airports.

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CLIMATE

CONCEPT

Many people think of weather and climate as concepts that are very nearly synonymous, but this is far from the truth. Whereas *weather* is a term referring to the atmospheric conditions for a particular place at a particular time, *climate* describes the overall weather pattern of a region over an extended period. A spot on the South Carolina coast, for instance, is likely to be humid and prone to hurricanes; another place, in the Rocky Mountains, might be dry and windy; while yet another locale, in Hawaii, most likely is inclined to extremely mild and equable or unvarying temperatures. In each case, what has been described is climate; for the weather in any of those particular places, one would need to check the weather report on a specific day. Despite the fact that climate is a concept that encompasses the weather in a region over an extended period, it is still possible for climate itself to vary.

HOW IT WORKS

The Atmosphere

All weather takes place in the atmosphere, the uppermost of the four earth systems. A blanket of gases created in large part by the expulsion of elements from the geosphere through volcanic eruptions, the atmosphere sustains the biosphere through its components of oxygen and carbon dioxide. But it also recirculates water from the hydrosphere, a key function in its role as a weather-generating system. (See Earth Systems for more about the interactions among geosphere, biosphere, hydrosphere, and atmosphere.)

COMPOSITION OF THE ATMOSPHERE. Though we think of the atmosphere as being composed primarily of oxygen, the vast majority of it (78%) is nitrogen. The latter is a highly unreactive gas, meaning that it does not tend to bond chemically with other elements. (Nitrogen itself is discussed in considerably greater detail within the essay Nitrogen Cycle.) Therefore, the nitrogen in our air is really just "filler," the result of volcanic eruptions billions of years ago: unlike carbon dioxide, which dissolved in the water of Earth's oceans, the nitrogen simply stuck around in the atmosphere.

Air is not a chemical compound but a mixture, of which nitrogen and oxygen together account for 99%. Another 0.93% is argon, which is a noble gas, meaning that it, too, is highly unreactive. The last 0.07% comes from trace gases (i.e., gases in very small quantities), including two that are extremely important to the operation of Earth: carbon dioxide and water vapor. The first of these is a key component in the biosphere and in biogeochemical cycles (see Carbon Cycle), while the second is of enormous importance in weather and climate.

The Troposphere and Air

It may be surprising to learn that water vapor is such a small portion of the atmosphere; even more shocking is the tiny fraction that this amount of water (equivalent to many billions of gallons) constitutes in proportion to Earth's entire water supply. Furthermore, all our weather, which plays such an integral role in our lives, is generated in a very small portion of the atmosphere.



FOR EVERY CLIMATE REGION ON EARTH, THERE ARE PARTICULAR TYPES OF PLANTS AND ANIMALS THAT HAVE ADAPTED TO THE PREVAILING CONDITIONS. ANIMALS THAT LIVE IN POLAR REGIONS, LIKE THIS BEAR, TYPICALLY HAVE VERY SMALL EARS, GIVING THEM LESS SURFACE AREA TO EXPOSE TO THE COLD; THEY ALSO TEND TO HIBERNATE AS A MEANS OF ENDURING THE WINTER. *(© John Shaw/Photo Researchers. Reproduced by permission.)*

This is the troposphere, the lowest layer, which extends to about 10 mi. (16 km) above the surface of Earth. The height of the troposphere is about one-fifth the combined height of the troposphere, stratosphere, and mesosphere, the three atmospheric layers that contain air. (Beyond these layers are the thermosphere, which eventually dissolves into the exosphere and the emptiness of space, which is characterized precisely by its lack of an atmosphere.)

A HIGH CONCENTRATION OF AIR. Small as the troposphere is within the larger atmosphere, however, it contains 80% of the atmosphere's mass. The reason is that at higher altitudes, Earth exerts less gravitational attraction on the gas molecules that make up air. Thus, if one were to travel up through the outer layers, the amount of air in the atmosphere would simply shrink to nothingness because at that height, Earth does not exert enough gravitational force to hold in place those ultralight particles.

By contrast, in the troposphere, the gravitational force—a function of the distance between two objects, in this case, a gas molecule and Earth—is extremely strong. This results in a high concentration of gas near the surface. (Note the term *gas*: remember that air is a mixture, not a compound, so there is no such thing as an "air molecule." Instead, there are only molecules of oxygen [O_2], ozone [O_3], nitrogen [N_2], carbon dioxide, and water, as well as atoms of argon and other noble gases.)

In any case, the high concentration of gas creates pressure, which, along with several other factors, causes air to move. The result is weather, and weather patterns over a long enough period of time yield what we call climate. (See Weather for more about the components that make up weather as well as their interactions.)

THE ATMOSPHERIC SCIENCES

Weather is like a daily newspaper, whereas climate is like a book of history: whereas weather reflects the atmospheric conditions for a particular place at a particular time, climate is the overall pattern of weather over an extended period. This difference is reflected in the organization of the atmospheric sciences, the area of earth sciences concerned with atmospheric phenomena.

Principal among the atmospheric sciences are meteorology, which is the study of weather,

and climatology, or the study of climate. Meteorology focuses on daily or even hourly changes in conditions within the troposphere and the lower stratosphere, the region just above it. By contrast, climatology is concerned with analyzing the weather in a particular area over periods as short as a month or as long as several million years.

Whereas meteorology involves daily weather forecasts and reports, efforts in climatology are directed toward explaining differences in climate around the earth. Climatologists also investigate how these differences are related to other aspects of the natural environment. Paleoclimatology is a specialized branch of climatology devoted to the study of climatic conditions in the distant past. Such study may require investigation of fossils and other materials that provide physical or chemical clues regarding the past climate and changes it experienced.

REAL-LIFE APPLICATIONS

CLIMATES ZONES AND ORGANISMS

One of the few ancient scientific thinkers whose work is still held in high regard was the Roman geographer Pomponius Mela (*fl. ca.* A.D. 44). In *De situ orbis,* Mela introduced the idea of five climate zones on Earth: northern frigid or cold, northern temperate or mild, torrid (very hot), southern temperate, and southern frigid. In a world that knew of no lands further north than Scandinavia (a semi-mythical place the Greeks had called "Thule") or further south than the lower Nile, Mela's designation of climate zones was extraordinarily accurate.

Only in the 1910s did the Russian climatologist Wladimir Köppen (1846–1940) improve on Mela's system, developing his own five-part climate designation. By Köppen's time, it was clear that there was not necessarily any climatic difference between northern and southern seasons, except inasmuch as the seasons in the Southern Hemisphere took place at opposite times of the year from those in the Northern Hemisphere. Therefore, he dispensed with all references to latitude except insofar as they related to position relative to the equator.

LARGE CLIMATE REGIONS. The Köppen system recognizes the zones of humid tropical, dry, humid mid-latitude with mild winters, humid mid-latitude with cold winters, and polar. Each of these larger categories is then subdivided into smaller climate types: for example, among the dry-climate group, there is a distinction between deserts and steppes, which are arid but not completely barren plains of a type found in Russia and central Asia.

Two factors, the average annual temperature and amount of precipitation, serve to differentiate climate types. Humid tropical, dry, and polar zones are fairly self-explanatory; as for the two humid mid-latitude types, they are distinguished by their distance from the equator. For instance, the southern United States would be an example of a humid mid-latitude region with mild winters, while the northeastern United States—New York and New England—would be considered a humid mid-latitude region with cold winters.

For every climate region on Earth, there are particular types of plants and animals that have adapted to the prevailing conditions. Animals that live in desert regions, for example, might have large ears to add a greater surface area for perspiration. On the other hand, animals in polar regions typically have very small ears, giving them less surface area to expose to the cold. Both camels and cacti are organisms well adapted to a desert climate: the camel can store large amounts of water and food in its hump, while the cactus requires little moisture to survive. Many a desert animal is nocturnal, allowing it to survive the heat, while most polar animals tend to hibernate as a means of enduring winter.

MICROCLIMATES

Not all climates necessarily spread across a whole desert or mountain range—or, in the case of Antarctica, with its decidedly polar climate, a whole continent. A very specific area either on Earth's surface or just a few feet or meters above or below it (i.e., up in the trees or in the soil) likewise can have its own microclimate. The very existence of a microclimate, with all its complexity, serves to show just how complex the larger Earth system is.

A particular microclimate, such as that of a forest or even a particular spot within a forest, has its own specific weather conditions: temperature, humidity, wind patterns, dew, frost, and evaporation or transpiration. Soil is a major factor influencing the quality of the microclimate: if the soil



BENI ABBES DUNES, SAHARA DESERT. SOIL IS A MAJOR FACTOR INFLUENCING THE QUALITY OF A MICROCLIMATE: SOIL THAT IS SANDY IN TEXTURE AND LIGHT IN COLOR IS LIKELY TO REFLECT MORE LIGHT AND HEAT. *(© V. Engelbert/Photo Researchers. Reproduced by permission.)*

is sandy in texture, it is likely to reflect more light and heat. The same is true if it is light in color. Also important is topography, an example being the rain shadow created by mountains. (See Mountains for an explanation of rain shadows.)

MICROCLIMATES IN ACTION. A beautiful example of microclimate in action can be found when hiking on Mount Santo Tomas outside Baguio in the northern Philippines. Nestled in the mountains, with still higher regions such as Santo Tomas nearby, Baguio has long been a popular resort owing to its cool temperatures. It is one of the few places in the Philippines where one can find evergreen conifers such as pine trees, and the semi-alpine climate makes Baguio a welcome relief from the heat of Manila and other regions further south.

Even though it lies in the northern portion of Luzon, the northernmost of the major islands in the Philippine archipelago, it is not latitude that gives Baguio its cool climate; instead, it is altitude. The same is true of other places around the world: Quito, Ecuador, for instance, which has an extremely cool climate because it is high in the Andes, even though it lies on the equator. (The 2001 movie *Proof of Life,* which portrays climatic conditions ranging from mild to cold, was filmed in and around Quito.)

On Santo Tomas, however, where the altitude is even greater than that of Baguio, it is pos-

sible to experience both the heat that characterizes most of the Philippines *and* the cool conditions of the mountains in northern Luzon. Standing at a particular spot along the mountainside, one can feel the heat that falls directly on the mountain, owing to its tropical latitude—which means that the sunlight reaches the surface at a more or less perpendicular angle. At the same time, one can feel the cool breeze that blows up the mountain as the result of its altitude. It is possible, in fact, to stand in such a way that one's back, to the mountain itself, is hot and sweaty while one's face enjoys the cool, moist highland breeze.

CAN CLIMATE CHANGE?

Though we have established that climate is a long-term weather pattern, that does not mean that climate itself is fixed and unchanging. Any number of factors can affect it. For example, the "fog" in London was once such an established fact that it became associated with that city in the way that wind is with Chicago.

But just as Chicago's status as the "Windy City" is something of a myth (in fact, there are more than a dozen cities more windy, though Chicago does experience powerful winds as a result of its proximity to Lake Michigan), the London fog was not actually what it seemed to be. The fog was not really fog at all but pollution produced by the burning of coal for heat. As coal gave way to gas and other types of heat during the twentieth century, the fog in London's climate changed.

HEATING UP OR COOLING DOWN? A less advantageous condition in the global climate may be a result of other technological changes, according to some scientists. The burning of fossil fuels, such as coal, natural gas, and petroleum, during the past century or more has put large amounts of carbon dioxide into the atmosphere. That part of the situation is fairly cut and dried; as to the potential result, the scientific community is divided.

Some scientists believe that higher concentrations of carbon dioxide will lead to a greater retention of heat in the atmosphere, resulting in a higher annual average global temperature. This phenomenon, known as global warming, has attracted considerable media attention owing to its promotion by environmental activists, including celebrities who embrace environmental causes. Yet the global warming position is far from the only interpretation that the facts suggest.

Other experts contend that high levels of carbon dioxide in the atmosphere will have the opposite effect. According to this view, the concentration of carbon dioxide may heat the atmosphere in the short term, but this will result only in a larger amount of evaporation from the oceans. This evaporation, in turn, will result in the formation of much larger cloud masses, which would have the effect of reflecting sunlight back into space—thus, in fact, *lowering* Earth's temperature.

The global warming position, with its media and celebrity support, has held the lead since the 1980s. For this reason, it is easy to forget that in the mid- to late 1970s, many environmentalists held an exactly opposite position. At that time, a series of extremely cold winters led to the claim that Earth was *cooling* and that in a few more centuries, a new ice age would ensue. In fact, this is a considerably more plausible position, given the fact that Earth has experienced countless ice ages in the past.

BLOCKING OUT THE SUN. Of course, it could be maintained (as advocates of global warming do) that the present situation of massive fossil-fuel burning has never occurred in Earth's history. This is certainly true, but there is less credibility in the claim that never before has so much carbon dioxide been introduced to the atmosphere. In fact, billions of years ago, volcanoes belched vast quantities of the gas into the region above Earth's surface, but because carbon dioxide is highly water-soluble, most of it dissolved into the oceans' waters.

This points to one of the means by which a rapid climate change, in particular, a sudden cooling, is brought about: by a volcanic eruption or other phenomenon that places enormous amounts of dust and ash in the air. In so doing, it reduces the amount of solar radiation that reaches Earth's surface, causing temperatures to drop. An extreme example of this may have occurred about 65 million years ago, as the result of a meteorite hitting Earth and causing rapid climatic changes that brought about the mass extinction of the dinosaurs and other life-forms (see Paleontology).

A more benign example of atmospheric blockage occurred in 1991, after Mount Pinatubo in the Philippines erupted. The eruption appar-



NEW YORK CITY HAS A MASSIVE CONCENTRATION OF HUMANS, MACHINES, AND CONCRETE IN A VERY SMALL AREA. CITIES WITHOUT ADEQUATE GREEN SPACE, SUCH AS NEW YORK'S CENTRAL PARK (SHOWN HERE), BECOME GIANT REFLECTORS, AND THE PRESENCE OF SMOG AND HEAT FROM CARS AND OTHER MACHINES ADDS TO THE UNHEALTHY ENVIRONMENT. *(© Rafael Macia/Photo Researchers. Reproduced by permission.)*

ently released so much ash and other material into the atmosphere that it temporarily reversed a general warming trend that had prevailed during the 1980s. By the mid-1990s, however, the materials from Mount Pinatubo appeared to have settled out of the atmosphere, thus causing a return to early climate trends.

HEATING UP A MICROCLIMATE. Despite the questionable nature of some environmentalists' claims concerning the global climate, environmentalists are absolutely correct in noting the effects of human civilization, development, and technology on microclimates. An excellent example is New York City. Though it is located in the humid temperate climate zone described earlier, with cold winters, the city has less snowfall—and hotter summers—than less populated areas of New York State or even areas in Pennsylvania that lie on the same latitude.

The difference, of course, lies in the fact that New York City is one of the planet's greatest municipalities, a massive concentration of humans, machines, and concrete in a very small area. Heat-sensitive satellite imaging equipment routinely produces images of the United States that show great areas of heat around the major cities, particularly New York. Concrete, buildings, roads, and the like constitute what developers call impervious surface, meaning that rain is not supposed to leach through these surfaces to the soil; rather, it will remain on the surface as runoff. But sunlight cannot gather in puddles or run off into storm drains: it can only reflect, and thus a big city is a huge mirror to the Sun's rays.

A major city, from the standpoint of climate, is rather like a person who places a mirrored piece of metal around his or her face to "soak up the Sun's rays"—an extremely unhealthy, dangerous, and inadvisable practice. Cities without adequate green space, such as parks, become giant reflectors, and the presence of smog and heat from cars and other machines only adds to the unhealthy, artificially heated environment.

It is particularly unfortunate to see such changes in a city such as Atlanta, which until about 1980 was a fairly sleepy town noted for its abundance of trees. Atlanta has long since become a boomtown, and the trees of its metropolitan area are being massacred at an alarming rate. Not only is this denuding the city and suburbs (and in the process, some would say, stripping its last vestiges of charm), but it is raising Atlanta's average temperature—which was already high as a result of the city's latitude.

EARTH, SPACE, AND ICE AGES

If Earth were a horse on a carousel, with the Sun at the spinning center of the merry-go-round, the horse representing our planet would not be sitting upright, at a 90° angle to the carousel floor. Rather, it would be tilted off the perpendicular angle by 23.5°, a fact responsible for many features of the global climate and microclimates of Earth.

At certain times of the year, rays from the Sun strike either the Northern or Southern hemisphere more directly than at other times. Summer occurs in the Northern Hemisphere during the middle of the year, because, at that point in the planet's movement around the Sun, the rays of the Sun strike the Northern Hemisphere at an

KEY TERMS

ATMOSPHERE: In general, an atmosphere is a blanket of gases surrounding a planet. Unless otherwise identified, however, the term refers to the atmosphere of Earth, which consists of nitrogen (78%), oxygen (21%), argon (0.93%), and other substances that include water vapor, carbon dioxide, ozone, and noble gases such as neon (0.07%).

ATMOSPHERIC SCIENCES: A major division of the earth sciences, distinguished from geoscience and the hydrologic sciences by its concentration on atmospheric phenomena. Among the atmospheric sciences are meteorology and climatology.

CLIMATE: The pattern of weather conditions in a particular region over an extended period. Compare with *weather.*

CLIMATOLOGY: An area of the atmospheric sciences devoted to studying the weather in a particular region or regions over periods as short as a month or as long as several million years.

METEOROLOGY: The study of the atmosphere, weather, and weather prediction.

MICROCLIMATE: The climate of a very specific region a few feet or meters above or below Earth's surface. The size of microclimates is undefined and variable, but they are most definitely smaller than the regions (a state, a country, even a continent) over which a particular climate is said to prevail.

TROPOSPHERE: The atmospheric layer closest to the surface, extending upward approximately 10 mi. (16 km). The troposphere contains about 80% of the air in the atmosphere and is the region where weather occurs.

WEATHER: The condition of the atmosphere at a given time and place. Compare with *climate.*

angle close to the perpendicular. The same happens in the Southern Hemisphere around the end of the year, when that section of the planet receives solar radiation at a nearly perpendicular angle.

Another important factor that relates Earth's position in space to its climate and microclimates is its pattern of movement around the Sun. The carousel analogy is a flawed one, because a carousel is round; Earth's orbit, in fact, describes an ellipse, or oval. The reason is that the Sun exerts a greater gravitational pull on Earth at different parts of its orbital path, and the result is that at its closest approach to the Sun, Earth receives more solar energy than it does when it is farthest away from it. This has little do with seasons: the closest approach occurs in January, winter in the Northern Hemisphere. Conversely, in July, the hottest time of year for the Northern Hemisphere, Earth is at its furthest point from the Sun.

EXPLAINING ICE AGES. It is possible that Earth's position relative to the Sun may explain those dramatic periods of cooling known as *ice ages,* when much of Earth's water freezes, larger amounts of land are exposed, and some life-forms die off while new ones develop. There have been numerous ice ages in Earth's history, and what we call *the* Ice Age, which ended about 10,000 years ago, was just the last ice age.

That one was particularly significant, of course, not only because it was most recent, occurring as it did on the eve of civilization's beginnings, but because it was a formative juncture in human development. During those thousands of years, human hunter-gatherer society

and Paleolithic technology developed to its highest point. Also, many of the significant migrations of people took place, most notably the movement of Siberian tribes eastward across the land bridge of what is now the Bering Strait.

What causes ice ages and other large-scale climate changes? In the 1930s the Serbian astrophysicist Milutin Milankovitch (1879–1958) put forward a theory maintaining that changes in the pattern of Earth's orbit around the sun, as well as in Earth's inclination to the plane of its orbit, could explain these changes in climate. The planet's axis of inclination (that is, its angle in relation to the plane of orbit) changes over a period of about 22,000 years, a cycle known as the *precession of the equinox.* As a result, first one hemisphere and then the other is be pointed toward the Sun.

Milankovitch evolved a complex theory that took into account precession of the equinoxes, changes in the shape of Earth's orbit, and changes in its orbital tilt. The theory has been improved and modified numerous times since the 1930s, but, in general, Milankovitch's ideas still provide climatologists with a basic understanding as to how large changes in Earth's climate take place.

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INDEX OF EVERYDAY THINGS

The "everyday" items discussed in this series (volumes 1-4) have been categorized into 26 general subject areas, and are listed below. Boldface type indicates main entry volume and page numbers. Italic type indicates photo and illustration volume and page numbers.

AGRICULTURE

Ammonia fertilizers, 3:351
Ammonium nitrate, 3:351–352, 4:*333*
Angiosperm reproduction, 3:138, 3:140–141
Angiosperms, 3:173–174, 3:*362,* 3:*364,* 3:364–365, 4:347–349
Aphids, 3:388
Apple tree stomata, 4:*388*
Bull's horn acacia, 3:386
Burdock (plant), 3:389
Cabbage, 3:*26*
Cacti, 3:*351*
Cattle, 3:7–8, 3:123, 3:233
Chestnut blight, 3:394
Chickens, 3:322, 3:324, 3:328
Chlorophyll, 3:*4,* 3:5
Chloroplasts, 3:*4*
Crops, 3:136, 3:209, 3:350–352, 3:380
Delta soils, 3:351
Desert soil, 3:350, 3:*351,* 4:297–300
Domesticated animals, 3:387, 3:395–396
Dust bowls, 3:352, 4:270, 4:286, 4:*303,* 4:304–305
Epiphytic plants, 3:389
Fertilizers, 3:351
Greenhouse effect, 4:355–356
Gymnosperms, 3:138, 3:140, 3:173–174, 3:*364,* 3:364–365, 4:347–349
Humus, 4:*295*
Kudzu, 3:211–214, 3:274, 4:279–280
Lemons, 3:93
Limes, 3:93
Mad cow disease, 3:233
Minerals, 4:294
Mushrooms, 3:384–385, 3:*385*
Nitrogen cycle, 4:338
Oranges, 3:93
Orchids, 3:138, 3:385
Peas, 4:*199*
Pineapples, 3:*137*
Rice, 3:95
Rubber, 2:152, 2:267
Salt, 3:350
Seeds and seed-bearing plants, 3:138
Soil, 3:351–352, 4:270, **4:292–300,** 4:304–305
Soil conservation, 4:304–305
Soil formation, 4:294, 4:296
Spruce trees, 3:371
Topsoil, 4:295–296
Trees, 3:371–372, 3:374
Wheat, 3:352

ANIMALS

Aardvarks, 3:222
African black rhinoceros, 3:386, 3:*387*
Albatross, 3:338
Anteaters, 3:*223,* 3:223–224
Ants, 3:*349,* 3:349–350, 3:386, 3:388–389
Apes, 3:220–221, 3:274–275
Aphids, 3:388
Arachnida, 3:275
Arctic fox, 3:*394*
Arctic tern, 3:338
Artiodactyls, 3:223
Bats, 2:305, 3:141, 3:*170,* 3:220, 3:340
Bears, 3:*40,* 3:89
Beavers, 3:*322*
Bedbugs, 3:281–282
Bees, 3:211, 3:*211,* 3:303–304, 3:323–324
Bird colonies, 3:402, 3:*402,* 3:406
Bird parasites, 3:274, 3:330–331
Birds, 3:73, 3:309, 3:322–324, 3:327–331, 3:*329*
Birds, aerodynamics of, 2:103–105, 2:115
Black-throated green warblers, 3:217
Butterflies, 3:338, 3:388–389
Camels, 3:223, 4:*307*
Cardinals, 3:327
Carnivores, 3:221, 3:361, 4:200, 4:342
Cats, 2:323, 3:298, 3:387
Cattle, 3:7–8, 3:123, 3:233

Cetaceans, 3:221–222
Cheetahs, 3:*373*
Chickens, 3:322, 3:324, 3:328
Chiropterans, 3:220
Class Insecta, 3:275
Cold-blooded animals, 3:218
Cowpox, 3:256–257, 3:*257*
DDT (pesticide), 3:*72,* 3:73, 4:358
Dermoptera, 3:220
Desert tortoises, 3:*351*
Detritivores, 3:69, 3:221, 3:361, 4:294, 4:316–317
Detritivores in food webs, 3:68, 3:349, 4:200, 4:342
Dodo (bird), 3:208–209, 3:*209*
Dog whistles, 2:323
Dogs, 2:323, 3:298, 3:303, 3:383, 3:387
Dolly (cloned sheep), 3:*122,* 3:123
Dolphins, 3:195, 3:204–205, 3:221–222, 3:340–341
Domesticated animals, 3:387, 3:395–396
Donkeys, 3:215
Ducks, 3:193, 3:330
Dust mites, 3:*265*
Earthworms, 3:349
Egg-laying mammals, 3:218
Elephants, 3:200, 3:222
Endangered or extinct bird species, 3:208–209, 3:*209,* 3:408
Endangered species, 3:208
Eskimo curlews, 3:208
Felidae, 3:221
Field mice, 3:163–164
Fish, 2:122
Fleas, 3:282
Frigate birds, 3:*145*
Gazelles, 3:*373*
Geese, 3:322, 3:328–330, 3:*329*
Gills, 3:57
Hares, 3:226
Herons, 3:*375*
Hinnies, 3:215
Hookworms, 3:278
Horses, 3:172–173, 3:215, 3:222, 3:*402,* 4:343–344
Insectivores, 3:219–220
Insects, 3:165, 3:275, 3:279–282
Invisible fences, 2:323
Jellyfish, 3:*321*
Kangaroo rats, 3:329–330
Kangaroos, 3:219, 3:*219*
Kingdom animalia, 3:198, 3:205, 3:206
Lemurs, 3:220
Lice, 3:282
Lift (aerodynamics), 2:104–105
Llamas, 4:*344*
Loa loa, 3:279
Lobsters, 3:*171*
Locusts, 3:*405*
Loggerhead turtles, 3:338–339
Mad cow disease, 3:233
Mammals, 3:58, 3:195, 3:204–205, 3:217–226
Manx shearwaters (bird), 3:338
Marsupials, 3:218–219, 3:*219*
Mating rituals, 3:*145,* 3:145–147
Methane, 3:7–8
Mice, 3:123, 3:163–164, 3:226
Minnows, 3:327–328
Moles, 4:296–297
Moths, 3:138, 3:173
Mules, 3:215, 3:*216*
Mussels, 3:71, 3:211
Nematoda (phylum), 3:349
Nile perch, 3:210
Northern fur seal, 3:*130*
Northern spotted owls, 3:406, 3:408, 4:*354,* 4:354–355
Omnivores, 3:361
Owls, 3:406, 3:408
Oxpeckers, 3:386, 3:*387*
Parasites, 3:274, 3:279–282, 3:330–331
Pepper moths, 3:173
Pesticides, 3:*72,* 3:73
Pigeons, 3:338
Pinworms, 3:278
Polar bears, 3:89, 4:*406*
Pollinating plants, 3:140–141
Porpoises, 3:221, 3:340–341
Prairie dogs, 4:*297*
Pregnancy and birth, 3:151–153
Primates, 3:167–168, 3:205–206, 3:216, 3:220–221
Rabbits, 3:226
Rabies, 3:257
Rats, 3:226, 3:330
Rhinoceros, 3:386, 3:*387*
Right whales, 3:208
Rocky Mountain bighorn sheep, 3:*323*
Rodents, 3:224–226
Roundworms, 3:278
Ruminants, 3:7–8, 3:53
Salmon, 3:*337*
Sea otters, 3:71
Seals, 3:*130*
Sewage worms, 3:72
Shedding (fur or skin), 3:313, 3:*313*
Sheep, 3:*122,* 3:123, 3:*323*
Shrews, 3:219–220, 3:226
Snails, 3:*298,* 3:333
Soil, 4:*297*
Spiders, 3:330, 3:*332*
Sponges, 3:*199*
Spotted owls, 3:406, 3:408, 4:*354,* 4:354–355
Squirrels, 3:*112,* 3:113
Starfish, 3:*70,* 3:71
Stickleback fish, 3:217, 3:322, 3:327
Stingrays, 4:*121*
Suriname toad, 3:*152*

Swallows, 3:338
Tapeworms, 3:277–278
Taxonomic keys, 3:193
Teeth, 3:222
Termites, 3:6, 3:*6*
Tickbirds, 3:386, 3:*387*
Ticks, 3:*279,* 3:282
Toads, 3:123, 3:*152*
Tortoises, 3:*351*
Training birds, 3:338
Trees, 3:363
Tubificid worms, 3:72
Turtles, 3:338–339
Vampire bats, 3:220
Whales, 3:195, 3:204–205, 3:*207,* 3:208, 3:222
Whales, echolocation by, 3:*339,* 3:340–341
Wings, 2:103–105, 2:115, 3:192
Worms, 3:*138,* 3:274–275, 3:277–279, 3:349, 4:296
Zebra mussels, 3:211
Zooplankton, 3:336

ART

Beauty, 3:*146,* 3:147
Colors, 2:355, 2:359–360
Diffraction, **2:294–300,** 2:356
Holograms, 2:*295,* 2:*296,* 2:298–300
Laser etching, 2:364
Light, 2:358–360
Primary colors, 2:360

AUTOMOBILES

Aerodynamics, 2:109–111
Airbags, 1:56, 1:58–59, 2:43, 2:189–190
Automobile industry, 1:176
Axles, 2:162–164
Brakes, 2:55, 2:62
Car horns, 2:336
Car jacks, 2:142–143, 2:167–168
Car lifts, 2:*160*
Carburetors, 2:117
Catalytic converters, 1:*305,* 1:307
Centripetal force, 2:46–48
Chrysler PT Cruiser, 2:109
Clutches, 2:55
Collisions, 2:41–43, 2:62–63
Combustion engines, 1:*51,* 1:292
Conservation of energy, 2:27
Crash tests, 2:*63*
Crumple zones in cars, 2:41–43
Drafting (aerodynamics), 2:109
Drag (aeronautics), 2:109–110
Electric vehicles, 1:*163*
Engine coolant, 2:248
Engine torque, 2:90
Ethylene dibromide, 1:234
Fossil fuels, 4:201–202
Friction, 2:*53,* 2:55
Fuel-injected automobiles, 1:56
Gas laws, 2:188–190
Gasohol, 3:30
Highways, 3:380
Lift (aerodynamics), 2:109–110
Nissan Hypermini, 1:*163*
Racing cars, 2:109–110
Radiators, 2:248
Roads, 2:48
Shock absorbers, 2:266–267
Tires, 2:*53,* 2:55
Torque, 2:90

AVIATION

Aerodynamics, 2:102–103, **2:102–111**
Aeronautics industry, 1:*172*
Aerostat Blimp, 2:*127*
Air pressure, 2:146
Air resistance, 2:78–80
Airfoils, 2:105–107
Airplanes, 2:105–107
Airports, 3:312
Airships, 1:*254,* 1:257, 2:126–129
Balloons, 1:58–59, 2:105, 2:125–127, 2:129
Blimps, 2:105, 2:*127,* 2:129
Dirigibles, 2:105, 2:127–128
Drafting (aerodynamics), 2:109
Drag (aeronautics), 2:106
Flaps (airplanes), 2:106
Fluid pressure, 2:144
Gliders, 2:105, 2:115–116
Goodyear Blimp, 2:105, 2:129
Graf Zeppelin (dirigible), 2:127–128
Helium, 2:126
Hindenburg (dirigible), 1:*254,* 1:257, 2:105, 2:126, 2:128
Hot-air balloons, 1:55–56, 2:126, 2:*186,* 2:188
Hydrogen balloons and airships, 1:*254,* 2:105, 2:126–128
Jet engines, 2:*312*
Korean Air Lines Flight 007 shootdown (1983), 2:64
Lift (aerodynamics), 2:105–106
Mach numbers, 2:106–107, 2:305
Parafoils, 2:108
Propellers, 2:106, 2:116
Radar, 2:348–349
Radar ranges, 2:348
Spoilers, 2:110
Wind tunnels, 2:98, 2:107

Wings, 2:105–108
Zeppelins, 2:105, 2:127–128

CIVIL ENGINEERING

Abrasive minerals, 4:137
Airports, 3:312
Aluminum, 1:*152,* 1:*153,* 1:157
Aqueducts, 4:91–92
Arches, 4:14, 4:*15*
Archimedes screws, 2:166
Bridges, 2:250, 2:*280,* 2:285
Building materials, 1:176
Centrifuges, 2:*46,* 2:48–49
Chichén-Itzá (Mayan pyramid), 4:*146*
Chimneys, 2:116–117
Concrete, 2:151, 2:152
Doorbells, 2:336
Doors, 2:89
Egyptian pyramids, 2:162, 2:164–165
Expansion joints, 2:250
Fill dirt, 4:295
Galvanized steel, 1:188–189
Gateway Arch (St. Louis, MO), 2:79
Geodesic domes, 1:*247*
Homestake Gold Mine (SD), 4:212
Iron mines, 1:*183*
Mining, 4:*19,* 4:161–162
The Parthenon (Greece), 3:138
Pipes, 2:97, 2:112–113, 2:144
Pyramids, 2:162, 2:164–165, 4:36, 4:*146,* 4:147
Rebar, 2:151
Roman Coliseum (Italy), 4:*15*
Rust, 1:*283,* 1:285, 1:294
Seawalls, 4:401
Statue of Liberty (Ellis Island, NY), 1:*174*
Tacoma Narrows Bridge (WA) collapse, 2:*280,* 2:285

COMMUNICATIONS

AM radio broadcasts, 2:276–277, 2:345–346
Broadcasting, radio, 2:345–346
Communications satellites, 4:*55*
Dipoles, 1:47, 1:113
Eavesdropping devices, 2:325
FM radio broadcasts, 2:345–346
Listening devices, 2:*322*
Microwaves, 2:276–277, 2:282–283, 2:347–349
Radio broadcasting, 2:345–346
Radio waves, 2:259–261, 2:276–277, 2:282, 2:346–347, 2:366
Remote sensing, 4:57, 4:59
Satellites, 2:347–348, 4:*55,* 4:57, 4:59
Shortwave radio broadcasts, 2:346–347
Sunspots, 4:80
Television tubes, 2:369
Train whistles, 2:*302,* 2:303–304

COMPUTERS

Algorithms, 3:193
CD-ROMs, 2:364
Disk drives, 2:337
DNA (deoxyribonucleic acid) nanocomputer, 3:120
Grocery store scanners, 2:*296*
Landsat (satellite program), 4:57, 4:59
Magnetic recording devices, 2:*332,* 2:*333,* 2:336–337
Magnetic tape, 2:336–337
Nanocomputers, 3:120
Open systems, 3:345–346
Silicon, 1:372
Silicon wafers, 1:*223*

CRIME AND POLICE WORK

Bulletproof vests, 1:*375*
Bullets, 2:*79,* 2:80
DNA, 3:*20,* 3:21, 3:103–105, 3:*105*
DNA evidence, 3:108
Explosives, 3:351–352, 4:*333*
Fingerprints, 3:*20,* 3:105
Forensic geology, 4:19–21
Gunpowder, 1:292
Holmes, Sherlock (fictional detective), 4:20–21
Incendiary devices, 1:175–176
Kevlar, 1:*375*
Murder cases, 3:105, 3:108
Murrah Federal Building bombing (1995), 4:*333*
Oklahoma City (OK) bombing (1995), 4:*333*
Plants, 3:108
Rape cases, 3:108–109
Simpson, O.J., 3:105, 3:*105,* 3:108
Terrorism, 3:231, 3:251–252
World Trade Center (New York, NY), 1:*153*

ELECTRONICS

Amplification, 2:315
Amplitude, 2:313–314
Calibration, 1:9, 1:81
Conduction, heat, 2:220, 2:228, 4:186
Conductivity, electrical, 2:228
Conservation of electric charge, 2:30–31
Electric current, 2:21
Electrical conductivity, 2:228
Electromagnetic induction, 2:341
Electromagnetic sound devices, 2:336
Electromagnetism, 2:334, 2:341–342
Electron tubes, 2:345

Electron volts (unit of measure), 2:345
Holograms, 2:*295,* 2:*296,* 2:298–300
Lasers, 2:361–362, 2:363
Loudspeakers, 2:315, 2:320–321, 2:336
Magnetic recording devices, 2:*332,* 2:*333,* 2:336–337
Magnetic sound devices, 2:336
Magnetic tape, 2:336–337
Magnetrons, 2:348
Microphones, 2:336
Nanotechnology, 2:56
Silicon, 1:244, 1:372
Silicon wafers, 1:*223*
Solenoids, 2:332, 2:334
Solid-state lasers, 2:361–362
Television tubes, 2:369
Thermistors, 2:243
Thermocouples, 1:17, 2:243
Transducers, 2:322–323, 2:349

ENERGY

Energy, 2:170–180
Alternative energy sources, 4:202, 4:206
Aromatic hydrocarbons, 1:368
Atmosphere, 4:198
Batteries, 1:*163,* 1:164–165, 1:*291,* 1:296
Biomass, 4:200–201
Biosphere, 3:347–348, 4:199–201, **4:351–358**
Bouncing balls, 2:175–176
Calorie (unit of measure), 2:219, 2:229
Calorimeters, 1:18–19, 2:230–231
Candles, 2:46, 2:360–361
Chernobyl nuclear disaster (1986), 1:98, 1:*103*
Coal, 4:*324,* 4:326
Coal gasification, 1:*35,* 1:43, 1:46
Conduction, heat, 2:220, 2:228, 4:186
Conservation of electric charge, 2:30–31
Conservation of energy, 2:27–29, 2:174–176, 2:179–180
Cyclotrons, 1:201
Earth, **4:192–206**
Electromagnetic spectrum, 2:345
Entropy, 1:13–14, 2:222–223
Fossil fuels, 4:201
Gasohol, 3:30
Gasoline, 2:27, 2:248
Heat, 2:228–229, 4:185–186
Heavy water, 1:96
Human body, 3:10, 3:36, 3:308
Hydroelectric dams, 2:101, 2:176
Hydrogen, 4:202
Hydrogen fuel, 1:259
Hydrogen sulfide, 1:256, 4:320–321
Lithium batteries, 1:*163,* 1:164–165
Metabolism, 3:33–34, 3:44, 3:80
Nuclear energy, 2:177, 4:202, 4:206
Oil refineries, 1:*357*
Particle accelerators, 1:72
Petrochemicals, 1:257, 1:367–368, 4:160
Petroleum, 1:368, 3:28, 3:30, 4:158–160
Petroleum industry, 1:*357,* 1:358
Photosynthesis, 3:4–5, 3:68, 3:360–361
Plutonium, 1:201
Potential and kinetic energy, 2:174–177, 4:193
Power, 2:173–174, 2:260
Power lines, 2:250
Propane, 1:56
Propane tanks, 2:188
Radioactive waste, 1:98
Radium, 1:178–179
Ruby lasers, 2:369
Solar power, 4:*202*
Solar radiation, 4:197
Space shuttle fuels, 1:241, 1:*292,* 1:293–294, 4:85
Sun, 3:67–69, 4:74, 4:78
Temperature and heat, 1:11, 4:193–195
Thermodynamics, 2:217–218, 2:222, 2:223
Tides, 4:197–198

ENVIRONMENT

Aerosol cans, 1:55, 2:187–188
Amazon rain forest, 3:365, 3:*366*
American chestnut trees, 3:394
American elm, 3:210
Angiosperms, 3:138–140, 3:173–174, 3:*362,* 3:*364,* 3:364–365, 4:347–349
Biodegradable plastics, 1:377
Biological communities, **3:391–399, 3:400–409**
Biological rhythms, **3:306–315**
Bioluminescence, 2:367, 2:369–370
Biomass ecosystems, 4:346
Biomes, **3:370–380**
Biosphere, **3:345–359,** 3:348, 3:360, 4:27, 4:341, **4:351–358**
Birds, 3:73
Blue-green algae, 4:*293*
Bogs, 3:376
Boreal forest, 3:362, 3:371–372
Cacti, 3:*351*
Carbon, **1:243–251,** 4:325–326
Carbon dioxide, 1:247–248, 1:268–269, 2:200, 3:28, 3:*28,* 3:369
Carbon dioxide in carbon cycle, 3:55–56, 4:326–329
Carbon monoxide, 1:248, 1:250, 1:301–302, 4:326–329, 4:328–329
Catalysts, **1:304–309,** 1:*305*
Chaparral, 3:375
Chernobyl nuclear disaster (1986), 1:*103*
Chestnut blight, 3:394
Chlorine, 1:231–232

Chlorofluorocarbons (CFCs), 1:233–234, 2:188
Chlorophyll, 3:*4,* 3:5
Chloroplasts, 3:*4*
Circadian rhythms, 3:306, 3:307–312, 4:83–84
Circannual cycles, 3:313
Climax biological communities, 3:370–371, **3:400–409**
Climax (ecology), 4:352
Cloud forests, 4:*345*
Colorado River delta, 4:*56*
Communities (animals), 3:323–324, 3:331
Coniferous forests, 3:371–372, 3:374
Conservation laws, **2:27–33**
Coral reefs, 3:377, 3:*377,* 4:*327*
Corrosion, 1:294
Cosmic background radiation, 1:*240*
Crater Lake (OR), 4:*259*
Currents, 4:*363,* 4:363–364
DDT (pesticide), 3:*72,* 3:73, 4:358
Deciduous trees, 3:362, 3:373
Decomposition, 3:68, 3:69
Deforestation, 3:365–366, 4:57, 4:59, 4:352–356, 4:*353*
Dendochronology, 4:119
Desertification, 3:353, 4:306–310
Desmodus rotundus, 3:220
Dinoflagellates, 2:369–370
Dodo bird and dodo tree, 3:208–209, 3:*209*
Dutch elm disease, 3:210
Ecology, **3:360–369,** 3:391, **4:351–358**
Endangered species, 3:207–208, 3:208, 3:223
Erosion, 3:352, **4:264–272,** 4:*284*
Erosion prevention, 4:270, 4:271–272, 4:305
Estuaries, 3:377
Fens, 3:376
Fir trees, 4:*318*
Forest conservation, 3:363, 3:408–409
Forest ecology, 3:362–363
Fungi, 3:198, 3:361, 3:384–386
Gas laws, 2:188–190
Grasslands, 3:374–375
Great Lakes (North America), 3:211, 3:354
Greenhouse effect, 3:366, 3:368–369, 4:355–356
Gymnosperms, 4:347–349
Ice ages, 4:381–384, 4:411–412
Ice domes, 4:378
Ice sheets, 4:378–379
Ice shelves, 4:*377,* 4:379
Indian pipe (plant), 3:385
Inuit, 3:*207*
Islands, 4:251–252
Kelp forests, 3:71
Lake Erie, 3:354, 4:318
Lakes, 3:210–211, 3:354, 3:375–376
Leaves, 4:*295*
Lichen, 3:386
Lilac, 3:*355*
Litmus paper, 1:314
Logging and forestry, 3:363, 3:365–366, 3:403, 3:406–408
Madagascar, 3:138, 4:*353*
Mangrove forests, 3:*362,* 4:346
Mariana Trench, 2:124–125
Meteorites, 3:185–186, 3:*186*
Mid-ocean ridges, 4:*221,* 4:222–223, 4:257
Mississippi River, 4:*365,* 4:365–366
Mohave Desert, 3:*351*
Moles (animals), 4:296–297
Montane forests, 3:363
Moss, 3:137
Mud cracking, 4:*287*
Mycorrhizae, 3:384–386
National parks, 3:363
Native Americans, 3:127, 3:130–131, 3:186, 3:*207,* 3:396
Northern spotted owls, 4:*354,* 4:354–355
Oceans, 3:182, 3:185, 3:336
Old-growth forests, 4:354–355
Orchids, 3:138, 3:385
Passionflower, 3:389
Pesticides, 3:*72,* 3:73
Phosphorus, 3:348, 3:384
Phytoplankton, 3:77, 3:376
Plants, 4:355
Pollen, 3:138–141, 3:*364,* 3:364–365, 4:347–349
Pollution, 3:240–241, 3:403
Ponds, 3:375–376
Porpoises, 3:221, 3:340–341
Protozoa, 3:275–277
Radioactive waste, 1:98
Rain forests, 3:350, 3:392–393, 4:297, 4:346
Rain forests and climate, 3:362–363, 3:373–374
Rain forests, destruction of, 3:365, 3:*366,* 4:*353*
Rivers, 2:*96,* 2:97, 2:113, 3:376, 4:*56,* 4:268, 4:285, 4:300, 4:374–375
Sahara Desert, 3:353, 4:306–307
Sahel region, 4:307
Savannas, 3:*373,* 3:374–375
Sequoia National Park, 3:363
Ships, 3:210
Soil, 3:385–386, 4:268, **4:292–300,** 4:301–302
Soil conservation, 3:352, **4:301–310**
Spotted owls, 3:406, 3:408, 4:*354,* 4:354–355
Spruce trees, 3:371
Streams, 3:376
Subpolar forests, 4:346–347
Subpolar glaciers, 4:378
Subsoil, 4:296
Sulfur, 3:348, 4:318, 4:*318,* 4:320–322
Summer, 3:358
Sun, 4:384
Swamps, 3:*375,* 3:376
Temperate deciduous forests, 3:373

Temperate forests, 4:346–347
Temperate rain forests, 3:373–374
Thermal expansion, 2:245–246, 2:249
Trees, 2:315, 3:*362,* 3:385, 3:406, 3:408
Trees, conifer, 3:371–372, 3:374
Trees, deciduous, 3:373
Trees and ecosystems, 3:209–210, 3:362
Tundra, 3:374, 3:392–395, 3:*394*
Volcanoes, 4:123, 4:126–127
Wetlands, 3:376
Worms, 3:275, 3:277–279, 3:349, 4:296
Yeast, 3:28, 3:*28*
Yellowstone National Park, 3:363
Zebra mussels, 3:211

FOOD AND DRINK

Acid reflux, 3:48
ADA (American Dietetic Association), 3:96
Alcohol, 1:356–357, 1:369, 3:27–28, 3:59
American diet, 3:49–50, 3:79
Amino acids, **3:11–17**
Antacids, 1:322–323, 3:48
Artichokes, 3:6
B vitamins, 3:92
Bacteria, 3:285
Bags, potato chip, 2:188
Baking soda, 1:315–317, 3:48
Beer, 1:*340,* 1:356–357
Beta-carotene, 3:90
Bingeing, 3:39
Boiling points, 1:39
Bowel movements, 3:50
Bread, 3:28, 3:*28*
Breast-feeding, 3:73
Brine-curing recipes, 1:352
Cabbage, 3:*26*
Calcium carbonate, 3:*377,* 4:327, 4:*327*
Calorie (unit of measure), 2:219, 2:229
Candy bars, 3:10
Carbohydrates, **3:3–10,** 3:44, 3:*79,* 3:80, 3:81, 3:82
Carbonated water, 1:248
Cereal foods, 3:81
Cholesterol, 3:*36,* 3:36–37
Citric acid, 1:*312,* 1:315
Citrus fruits, 3:93
Convection cooking, 2:348
Corn, 3:82, 3:387
Cream, 2:49
Dehydrating fruits, 1:351
Dextrose, 3:3–4
Digestive system, 3:*51,* 3:51–54
Dinuguan (Filipino delicacy), 3:302–303
Disaccharides, 3:4
Distillation, 1:40, **1:354–360,** 1:*357,* 2:209–210
Distilled water, 1:356
Drinking water and fluoridation, 1:233
Dry ice, 4:*402*
Eating habits, 3:39, 3:48, 3:242, 3:311
Emulsifiers, 1:333–334, 1:342–343
Enzymes, 3:24
Ethanol, 1:*340,* 1:343, 1:356–357
Fast food, 3:79, 3:81
Fats and oils, 3:35–37, 3:44–45, 3:81, 3:88, 3:297
Fiber in human diet, 3:50
Fried foods, 3:81
Health or organic foods, 3:86
Junk food, 3:10, 3:79
Lactose, 3:4
Lemons, 3:93
Limes, 3:93
Malnutrition, 3:82–86, 3:89
Maltose, 3:4
Meat, 3:23, 3:49–50, 3:277–278, 3:303
Meat preservation, 1:351–353
Milk, 1:*177*
Minerals, 3:80–81
Monosaccharides, 3:3–4
Mushrooms, 3:384–385, 3:*385*
Mussels, 3:71, 3:211
Oil emulsions, 1:333–334, 1:*339,* 1:342, 1:347–348
Oligosaccharides, 3:4
Oranges, 3:93
Organic and health foods, 3:86
Overweight Americans, 3:10, 3:37, 3:81, 3:*82,* 3:85–86
Phosphorus, 3:91
Pineapples, 3:*137*
Plants, 3:6–8, 3:23
Polysaccharides, 3:4
Pork, 3:277–278
Potato chip bags, 2:188
Preservation, 1:351–353
Proteins, 3:6, 3:13, 3:15, **3:18–23,** 3:44, 3:100–101
Proteins in nutrition, 3:10, 3:79–82
Recommended daily allowances (RDA), 1:125–126
Rice, 3:95
Salts, 1:352–353
Saturated fats, 3:36, 3:88
Sauerkraut, 3:*26*
Sodium, 1:166–167
Sodium substitutes, 1:165
Soft drinks, 1:*248*
Starches, 3:6–7, 3:*7,* 3:25
Sucrose, 1:109, 3:4
Sugar, 1:109
Sugars, 3:3–4, 3:25
Sushi, 3:*302,* 3:303
Table sugar, 3:4
Trichinosis, 3:278
Truffles, 3:385, 3:*385*
USDA food pyramid, 3:81

Vitamins, 3:95–96
Wheat, 3:352
Yeast, 3:28, 3:*28*
Zinc, 1:*154,* 1:188–189

GEOLOGY

Abrasive minerals, 4:137
Alkali metals, 1:153, **1:162–170**
Alkalies, 1:310–311, 1:319
Alkaline earth metals, 1:153–154, **1:171–180,** 1:*174*
Alpine glaciers, 4:378
Aluminum, 1:101, 1:121, 1:*152,* 1:157, 1:295–296
Antimony, 1:226
Aquifers, 3:347
Arctic Ocean, 3:88
Arkansas River, 4:*372*
Aromatic hydrocarbons, 1:368
Arsenic, 1:225–226
Asbestos, 4:139
Barium, 1:177–178
Bedrock, 4:296
Berkelium, 1:203
Beryllium, 1:175
Biogeochemistry, **4:313–322**
Biosphere, 4:27
Biostratigraphy, 4:106
Bismuth, 1:158, 1:161
Boron, 1:216
Brimstone, 4:320
Bromine, 1:234
Cadmium, 1:189
Calcite, 4:*136,* 4:138
Calderas, 4:259, 4:*259*
Californium, 1:203
Canyons, 4:*106,* 4:*265,* 4:270
Cap rocks, 4:*159*
Carbonates (minerals), 4:134
Carborundum, 4:137
Cerium, 1:208
Cesium, 1:170
Chemical deposition, 4:287–288
Chilean earthquake (1960), 4:237
Chlorine, 1:231–232
Chromium, 1:192
Chronostratigraphy, 4:95, 4:106–108
Cinder cones, 4:258
Cirque glaciers, 4:378
Clay, 2:40–41, 4:*287*
Coal, 4:*324,* 4:326
Cobalt, 1:190–191
Composite cones (volcanoes), 4:258
Compound minerals, 4:131
Continental crust, 4:229
Continental shelves, 3:377
Coon Creek (WI) erosion, 4:286
Copper, 1:188, 1:289–290, 4:138–139
Crystaline minerals, 4:132–133, 4:144
Curium, 1:202
Deuterium, 1:95–97, 1:254–255
Diamond, 1:246, 4:137–138, 4:165, 4:325–326
Digital photography, 4:55–56
Divergence (plate tectonics), 4:224
Dysprosium, 1:210
Earthquakes, 1:240, 4:235, 4:*236*
Elements, **1:119–126**
Erbium, 1:209
Erosion, 4:*284*
Europium, 1:210
Evaporites, 4:290–291
Fossil fuels, 4:158–160
Geysers, 4:*196*
Gold, 1:*25,* 1:28, 1:30, 1:*182,* 1:187, 1:295, 4:138
Gold mining, 4:*19,* 4:161–162, 4:288, 4:290
Grand Canyon, 3:113
Great Lakes (North America), 3:211, 3:354
Gulf of California, 4:*56*
Gypsum, 4:138
Hafnium, 1:192
Halemaumau volcano (Hawaii), 4:5
Halogens, 1:229
Hanging valleys, 4:380
Hawaii, 4:5
Himalayas (mountain range), 4:224, 4:*246*
Homestake Gold Mine (SD), 4:212
Hydrocarbons, 4:157–158
Ice, 2:208, 2:*247,* 2:248–249, 4:285, 4:376–377, 4:381–384
Ice caps, 4:378, 4:379–380
Ice domes, 4:378
Ice sheets, 4:378–379
Ice shelves, 4:*377,* 4:379
Icebergs, 2:*204*
Igneous rocks, 4:148–149
Indium, 1:157–158
Industrial minerals, 4:162, 4:164–165
Infrared photography, 4:54
Iran earthquake (1755), 4:237
Iridium, 1:191
Iron, 1:190, 1:336, 2:332
Iron mines, 1:*183*
Islands, 3:402–403, 4:248–252, 4:*249*
Jewels, 4:165
Kennicott Glacier (AK), 4:*381*
Kettle lakes, 4:380
Krakatau (Indonesia), 4:259–260
Lake Erie (North America), 3:354, 4:318
Lake Victoria (Africa), 3:210
Landforms, 4:245–247
Landsat (satellite program), 4:57, 4:59
Lava, 4:*148,* 4:258

Lead, 1:158, 4:139
Lisbon earthquake (1755), 4:233–234
Lithium, 1:164–166, 3:302
Lithosphere, 4:188, 4:212–213, 4:229
Little Ice Age (1250-1850), 4:384
Loma Prieta (CA) earthquake (1989), 4:*233,* 4:235, 4:*236*
Los Angeles (CA), 4:18
Magnesium, 1:*172,* 1:175
Magnetic metals, 1:190–191, 2:331–332
Manganese, 1:194
Maps, 4:44, 4:47–49
Metal crystals, 2:151–152
Metal elasticity, 2:150–151
Metalloids, 1:147, 1:222, **1:222–228,** 1:223
Metals, **1:151–161,** 1:*152,* 1:153
Metamorphic rocks, 4:150, 4:*150,* 4:152–153
Meteor Crater (AZ), 4:*91*
Meteorites, 3:345, 4:*91*
Mica, 4:*150*
Mid-ocean ridges, 4:*221*
Millbrae (CA) mudflows, 4:*276*
Mineral cleavage, 4:136
Mineraloids, 4:135
Minerals, 3:71, **4:129–142,** 4:143–145, 4:155–156, 4:165, 4:288–291
Mining, 4:162
Moraines, 4:380
Mount Etna (Italy), 4:*148*
Mount Everest (Nepal), 2:*142*
Mount Katmai (AK), 4:30
Mount Kilimanjaro (Tanzania), 4:*254*
Mount Machhapuchhare (Himalayas), 4:*246*
Mount McKinley (AK), 4:*275*
Mount Pelée (Martinique) eruption (1815), 4:260
Mount Pinatubo (Philippines) eruption (1991), 4:260
Mount Saint Helens (WA), 4:30, 4:260
Mount Santo Tomas (Philippines), 4:407–408
Mount Tambora (Indonesia), 4:30
Mountain ranges, 4:256–257
Mountains, **4:253–263**
Muscovite, 4:139
Music, 4:17
Natural magnets, 2:331–332
Neon Canyon (UT), 4:*106*
Nesosilicates (minerals), 4:135
New Guinea, 3:396, 3:398
New Madrid (MO) earthquakes, 4:235
New York City (NY), 3:*247,* 3:378, 3:410, 3:*410*
Nickel, 1:*184,* 1:191
Nicola River Canyon (British Columbia), 4:*265*
Niobium, 1:192
Noble metals, 1:122
Nonmetals, **1:213–221**
Nonsilicate minerals, 4:133–135
Northeast Passage, 3:88
Novaya Zemlya (Russia), 3:88–89, 3:*89*
Ocean convection, 4:191
Oceans, 3:347, 3:376–377, 4:191, 4:363–364
Ogallala Aquifer, 4:373
Oil industry, 4:158–159
Ophiolites, 4:257
Ores, 4:161–162
Orphan metals, 1:156–158, 1:161, 1:222
Orphan nonmetals, 1:214, 1:219, 1:221
Osmium, 1:191
Palladium, 1:191
Petroleum, 1:368, 3:28, 3:30, 4:158–160
Petroleum industry, 1:*357,* 1:358
Phosphates (minerals), 4:134, 4:317
Phosphor, 2:369
Phosphorus, 1:219, 4:317–318
Photography, 4:55–56
Piedmont glaciers, 4:378
Pillars of Hercules (Mediterranean Sea), 4:5
Plate tectonics, 4:228
Platinum, 1:191–192
Plutonium, 1:201
Pohutu Geyser (New Zealand), 4:*196*
Polar glaciers, 4:378
Polonium, 1:226–227
Popocatepetl (volcano), 4:*257*
Potassium, 1:167, 1:170
Prince William Sound (AK) earthquake (1964), 4:235
Propane, 1:56
Quartz, 4:*136*
Radar, 4:56–57
Radium, 1:178–179
Radon, 1:239–240, 1:241
Rain shadows, 4:260
Red Sea, 4:224, 4:*225*
Reservoir rocks, 4:158
Rhodium, 1:191–192
River deltas, 3:351, 4:*56,* 4:268, 4:300
Rivers, 2:*96,* 2:97, 2:113, 3:376, 4:285, 4:374–375
Rocks, **4:143–153,** 4:*159,* 4:219–220, 4:*267,* 4:286, 4:292
Rocks and compression, 4:14, 4:*15*
Rocks, dating of, 4:39, 4:*99*
Rocks and minerals, 4:155–158
Roden Crater (AZ), 4:16
Ronne Ice Shelf, 4:379
Ross Ice Shelf, 4:379
Royal Gorge (CO), 4:270
Rust, 1:*283,* 1:285, 1:294
Ruthenium, 1:192
Sabine Pass (TX), 4:*160*
Sahara Desert, 3:353, 4:*407*
Sahel region, 4:307
Salt, 1:111, 1:230, 1:*230*
Samarium, 1:*207,* 1:208–209
San Andreas Fault (CA), 4:224

San Francisco (CA) earthquake (1906), 4:235
Sandstone, 4:*26*
Seal rocks, 4:158
Seamounts, 4:258
Seashores, 3:377
Sedimentary rocks, 4:149–150, 4:294
Sedimentary structures, 4:288
Sediments, **4:283–291**
Seismology, 4:233–237
Selenium, discovery of, 1:221
Shale, 4:*159*
Shansi (China) earthquake (1556), 4:237
Shield volcanoes, 4:258
Shores, sea, 3:377
Silicates, 1:224–225, 4:135–136, 4:145, 4:160–161
Silicon, 1:224–225, 1:363–364, 4:160–161
Silver, 1:187–188, 1:*293*
Sinkholes, 4:247
Slides, 4:266–267, 4:271–272, 4:276
Sliding friction, 2:53
Sodium, 1:166–167
Stone compression, 4:*15*
Stratovolcanoes, 4:258
Striations, 4:*106*
Strontium, 1:176–177
Subpolar glaciers, 4:378
Subsidence convection, 4:188, 4:190–191
Sulfur, 1:219, 1:221
Tambora (Indonesia) eruption (1815), 4:260
T'ang-shan (China) earthquake (1976), 4:236–237
Tectosilicates (minerals), 4:135
Tellurium, 1:226
Terbium, 1:209
Thallium, 1:158
Thorium, 1:198–199
Tidal waves, 3:185
Till (sediment), 4:380
Tin, 1:158
Titanium, 1:192
Transantarctic Mountains (Antarctica), 4:379
Transition metals, 1:136, 1:154–155, 1:181, **1:181–195,** 1:*182*
Transuranium actinides, 1:201–204
Transuranium elements, 1:133, 1:155, 1:201
Tributary glaciers, 4:380
Tritium, 1:97, 1:*253,* 1:254–255
Truk Lagoon (Micronesia), 4:*249*
Uplift, 4:248
Upwelling regions (oceans), 3:377
Uranium, 1:199–201, 1:*200*
Valleys, 4:379, 4:380
Vanadium, 1:192
Vesuvius (Italy) eruptions, 4:259
Villa Luz caves (Mexico), 4:320
Volcanoes, 4:*148,* 4:213–214, 4:228, 4:*257,* 4:257–260, 4:*259*
Volcanoes and climate, 4:30–31, 4:409–410
Western Deeps Gold Mine (South Africa), 4:212
Wind, 4:*269,* 4:269–270, 4:285
Yellowstone National Park (U. S.), 3:363
Zinc group metals, 1:188–190
Zirconium, 1:192

HOUSEHOLD PRODUCTS

Aerosol cans, 1:55, 2:187–188
Air conditioners, 2:219–220
Alkanes, 1:367–368
Alkenes, 1:368
Alkynes, 1:368
Appliances, 1:*374*
Bases, **1:310–318**
Biodegradable plastics, 1:377
Burglar alarms, 2:335
Calendars, 2:8
Caustic soda, 1:317–318
Chimney sweeps, 3:240, 3:*240*
Chimneys, 2:116–117
Chlorofluorocarbons (CFCs), 1:233–234, 1:307, 2:188
Cigarette lighters, 1:*206*
Containers and fluid pressure, 2:142
Filaments (light bulbs), 2:361
Fire extinguishers, 1:55, 2:*185,* 2:187
Fluorescent bulbs, 2:*367,* 2:369
Freon, 1:*231*
Grandfather clocks, 2:267, 2:*272,* 2:274
Halogen lamps, 1:234
Hydrochlorofluorocarbons (HCFCs), 1:55, 2:188
Hydrogen chloride, 1:256
Hydrogen peroxide, 1:109, 1:256
Incandescent bulbs, 2:360–361, 2:*367,* 2:369
Index cards, 2:119
Jar lids and thermal expansion, 2:250
Lamps, 2:360–361
Lanterns, 2:360–361
Lids and thermal expansion, 2:250
Light, artificial, 2:360–361, 3:311–312, 3:*312*
Light bulbs, 2:360–361, 2:*367,* 2:369
Liquefied natural gas (LNG), 2:*193,* 2:200–201
Liquefied petroleum gas (LPG), 2:200–201
Liquid crystals, 1:43, 2:212, 2:214
Lye, 1:317–318
Matches, 2:*54,* 2:56
Mercury thermometers, 1:16, 1:189, 2:250–251
Microwave ovens, 2:348
Mirrors, 2:361
Oil lights, 2:360–361
Ovens, microwave, 2:348
Pendulum clocks, 2:267, 2:*272,* 2:274
Petroleum jelly, 1:*366*
Pewter, 1:336

Phosphor, 2:369
Pianos, 2:*273,* 2:*313*
Picture frames, 2:136
Propane, 1:56
Propane tanks, 2:188
Propellants in aerosol cans, 1:55
Radiators, 2:248
Refrigerators, 2:219–220, 2:222, 2:*229,* 2:232
Septic tanks, 3:352, 4:306
Shopping carts, 2:74
Shower curtains, 2:117
Soap, 1:*330,* 1:334, 1:342–343
Soda cans, 1:54–55, 2:187
Thermostats, 2:251–252
Torches, 2:360
Ultraviolet lamps, 2:368–369
Velcro, 2:53
Venetian blinds, 2:164
Washing machines, 2:49
Wheelbarrows, 2:161–163
Wrenches, 2:86–89

MACHINES

Machines, 2:157–169
Air conditioners, 2:219–220
Axles, 2:162–164
Bevel gears, 2:163
Block-and-tackle pulleys, 2:164
Compound levers, 2:162
Compound pulleys, 2:164
Cranes, 2:164
Crystals, 2:322–323
Electric engines, 2:90
Electric thermometers, 1:17, 2:242–244
Electrical generators, 2:341
Engine coolant, 2:248
Fax machines, 2:267–268
Flywheels, 2:55, 2:89–90
Fossil fuels, 4:201–202
Fulcrums, 2:160–162
Gears, 2:163–164
Generators, electrical, 2:341
Gyroscopes, 2:*88,* 2:89–90
Helical gears, 2:163
Hydraulic presses, 2:98–99, 2:142–143, 2:160
Inclined planes, 2:18, 2:71, 2:159, 2:164–165
Levers, 2:*158,* 2:159–164
Lubrication, 2:56
Mechanical advantage, **2:157–169**
Microscopes, 3:*288*
Moment arm, 2:87–88, 2:160–162, 2:166
Motors, 2:27
Nanotechnology, 2:56
Pendula, 2:267–269, 2:281–282
Pendulum clocks, 2:267, 2:*272,* 2:274
Perpetual motion machines, 2:55, 2:158–159, 2:216, 2:223
Piezoelectric devices, 2:322–323
Pistons, 2:99, 2:167–169, 2:188–189
Pivot points, 2:86–87
Planetary gears, 2:163
Pulleys, 2:163–164
Pumps, 2:99, 2:166
Recording devices, 2:*332,* 2:*333,* 2:336–337
Screws, 2:55, 2:158, 2:165–167
Siphon hoses, 2:99
Sledges, 2:162
Springs, 2:263–264, 2:266
Spur gears, 2:163
Steam engines, 2:120, 2:163, 2:221–222, 2:231–232
Stepper motors, 2:337
Thermometers, 2:239–240, 2:249–251
Thermoscopes, 2:239
Toothed gears, 2:163
Torque converters, 2:90
Turbines, 2:101
V-belt drives, 2:163–164
Venturi tubes, 2:113
Waterwheels, 2:99–100, 2:163
Wedges, 2:165
Wheelbarrows, 2:161–163
Wheels, 2:162–164
Windmills, 2:163

MANUFACTURING

Alloy metals, 1:192
Alloys, 1:334, 1:336
Aluminum, 1:121, 1:*152,* 1:157, 1:295–296
Argon, 1:241
Atomizers and chimneys, 2:116–117
Automobile industry, 1:176
Bags, potato chip, 2:188
Brass, 1:188, 1:336
Bronze, 1:336
Carbon polymers, 1:372
Carboxylic acids, 1:315, 1:369
Catalysts, **1:304–309,** 1:*305*
Cation resins, 1:106
Cations, 1:101, 1:103
Celluloid, 1:377
Cerium, 1:208
Cesium, 1:170
Chemical bonding, 1:112–113, 1:232, 1:244–245, **1:263–272**
Cholesteric liquid crystals, 1:43, 2:213
Cigarette lighters, 1:*206*
Clay, 2:40–41, 4:*287*
Coinage metals, 1:187–188, 1:294–295
Crystal lasers, 2:369

Dry ice, 1:248, 4:*402*
Dye lasers, 2:361–362
Elastomers, 2:152
Industrial distillation, 1:357–358
Iron ore, 1:190
Liquid crystals, 1:43, 2:212, 2:214
Magnetic metals, 1:190–191, 2:331–332
Mills, 2:163
Misch metal, 1:*206,* 1:208
Neoprene, 1:378
Nylon, 1:*282,* 1:366, 1:378
Petrochemicals, 1:257, 1:367–368, 4:160
Petroleum industry, 1:*357,* 1:358
Pewter, 1:336
Plastics, 1:*364,* 1:*365,* 1:366–367, 1:375–380
Polyester, 1:378–380
Polymers, **1:372–380,** 1:*373,* 1:*379,* 2:152, 3:13, 3:18–19
Potash, 1:167, 1:170
Potato chip bags, 2:188
Raytheon Manufacturing Company, 2:348
Rubber, 2:*151,* 2:152, 2:267
Ruby lasers, 2:369
Silicon, 1:244, 1:372
Silicon wafers, 1:*223*
Silicones, 1:225, 4:161
Soda cans, 1:54–55, 2:187
Synthetic polymers, 1:*374,* 1:*375,* 1:377–379
Synthetic rubber, 1:377–378
Tungsten, 1:192

MEDICINE

Accidents, 3:231
Acid reflux, 3:48
Acne, 3:286
Adrenaline, 3:267–268
African AIDS epidemic, 3:250
African trypanosomiasis, 3:276
AIDS (Acquired immunodeficiency syndrome), 3:245, 3:250, 3:258–261, 3:*259*
Air pressure, 2:145–146
Alcohol, 3:59, 3:240
Allergies, 3:60, 3:264–268, 3:*265,* 3:364–365
Alternative medicine, 3:239
Aluminum, 1:124–125
Alzheimer's disease, 3:*233,* 3:233–235
American diet, 3:49–50, 3:79
American Dietetic Association (ADA), 3:96
Amino acids, **3:11–17**
Amniocentesis, 3:156
Amoebic dysentery, 3:276
Amoxicillin, 3:290–291
Anaerobic bacteria, 3:58
Anaerobic respiration, 3:58–59
Anaphylactic shock, 3:265, 3:267–268
Anemias, 3:*14,* 3:15–16, 3:268–269
Anesthetics, 3:154
Anorexia nervosa, 3:38–39
Antacids, 1:322–323, 3:48
Anthrax, 3:*250,* 3:251–252
Antibiotics, 3:13, 3:165, 3:290–291
Antibodies, 3:122–123, 3:263–264
Antihistamines, 3:267
Antioxidants, 1:294, 3:91
Apnea, 3:310
Arsenic, 3:78
Asbestos, 4:139
Atherosclerosis, 3:*36*
Attention (brain function), 3:307
Autoimmune diseases, 3:230, 3:242, 3:268–269
B vitamins, 3:92
Bacteria, 3:165, 3:284–285
Bacterial infection, 3:284–286
Bacterial ulcers, 3:48–49, 3:*49*
Basilar membrane, 2:318
Beriberi, 3:92–95
Beta-carotene, 3:90
Bile, 3:47
Bilirubin, 3:51
Bingeing, 3:39
Biological rhythms, **3:306–315**
Biorhythms (1970's fad), 3:315
Biotechnology, 3:119
Bipolar disorder and lithium treatment, 1:165
Blood, 3:56–57
Blood components, 3:19, 3:21, 3:47, 3:56, 3:263–264
Blood infections, 3:276–277
Blood pressure, 2:146–147, 2:305
Blood vessels, 3:*36*
Bone marrow, 3:263, 3:*263*
Bones, 2:152
Botulism, 3:252
Bowel movements, 3:50
Brain, 2:318, 3:168, 3:299, 3:306–307
Brain diseases, 3:232–235, 3:*233,* 3:302
Breast-feeding, 3:73
Breathing, 2:145–146, 3:56–58
Bronchial disorders, 3:60
Bulimia, 3:*38,* 3:38–39
Calcium, 1:176, 3:81, 3:91
Calcium carbonate, 3:*377,* 4:327, 4:*327*
Cancer, 3:21, 3:62, 3:132, 3:230, 3:238–241
Cancer biopsy, 3:239
Cancer treatments, 3:21, 3:239
Carbohydrates, **3:3–10,** 3:44, 3:*79,* 3:80–82
Carbon, 1:123, 3:78
Carbon dioxide, 3:55–56
Carcinogens, 3:238
Cardiovascular disease, 3:230, 3:232
Catabolism, 3:33, 3:34–35

CCK (Cholecystokinin), 3:10
Cellulose, 3:8
Centrifuges, 2:48–49
Cervix, 3:153
Cesarean section, 3:156–157
Chemotherapy, 3:239
Childbirth, **3:151–157,** 3:154
Children, 3:258, 3:301, 3:334
Cholera, 3:*247*
Cholesterol, 3:*36,* 3:36–37
Chromium, 3:78
Chromosomes, 3:99–100, 3:*102,* 3:111–112, 3:117, 3:126, 3:135
Chromosomes and DNA, 3:99–100, 3:135
Circadian rhythms, 3:306, 3:307–312, 4:83–84
Citric acid, 1:*312,* 1:315
Cleft palate, 3:128
Cloning, 3:*121,* 3:122–123
Cochlea, 2:317–318
Coenzymes, 3:25–26
Cold, common, 3:60, 3:286–287, 3:301–302
Colloids, 1:42, 1:69, 1:332–333, 2:210–211
Color perception, 2:359–360
Congenital disorders, 3:128–131, 3:*129,* 3:155–156, 3:232
Copper trace elements, 3:78
Cousins, 3:115–116
Cowpox, 3:256–257, 3:*257*
Creutzfeldt-Jakob disease, 3:128, 3:232–233
Cystic fibrosis, 3:62, 3:128
Dehydration, 1:350
Delayed sleep phase syndrome, 3:311
Dental health, 1:233
Designer proteins, 3:21–22
Dextrose, 3:3–4
Diabetes mellitus, 3:242–243
Diaphragms (anatomy), 2:315, 2:320–321
Diastolic pressure, 2:147
Digestion, **3:44–54**
Digestive disorders, 3:48–50
Digestive system, **3:44–54,** 3:*46,* 3:*51,* 3:276, 3:278, 3:285–286
Diploid cells, 3:99
Disaccharides, 3:4
Disease risk factors, 3:239–241
Diseases, **3:229–235**
Diseases of ethnic groups, 3:113, 3:127, 3:131, 4:344–345
Diseases, social impact, 3:230, 3:246–248
Diseases, unknown causes, 3:230, 3:232–235, 3:*233*
DNA evidence, 3:108
DNA in genes, 3:100–101, 3:117–119, 3:*118,* 3:126, 3:164–165
Dominant genes, 3:112–113
Doping agents, 1:226
Down syndrome, 3:126, 3:129, 3:*129*
Drugs, 3:120, 3:154, 3:242–243, 3:302, 3:307, 3:315
Duodenum, 3:47, 3:48
Dwarfism, 3:129
Ear infections, 3:290
Eardrums, 2:317
Ears, 2:316–318
Eating disorders, 3:*38,* 3:38–40
Eating habits, 3:39, 3:48, 3:49, 3:242, 3:311
Ebola virus, 3:250–251
Elephantiasis, 3:*278,* 3:279
Embryos, 3:152–153
Endogenous infection, 3:283
Enterobiasis, 3:278
Enzymes, 1:306–307, 3:21, **3:24–30,** 3:37, 3:119
Epinephrine, 3:267–268
Epsom salts, 1:175
Escherichia coli bacteria, 3:*51,* 3:285–286
Esophagus, 3:45
Eustachian tubes, 2:317
Exhalation (human breathing), 3:55–56
Exogenous infection, 3:283
Eye diseases, 3:279
Eyes, 2:359–360
Facial characteristics, 3:*129,* 3:129–130
Fat, human body, 3:10, 3:35–37, 3:*36,* 3:88, 3:127, 3:*146,* 3:147, 3:307
Feces, human, 3:50–54
Flatulence, 3:54
Fluoride, 1:233
Fluorine, 1:232–234, 1:269
Forceps, 3:153–154
Fruits and vegetables, 3:93
Genetic disorders, 3:*113,* 3:113–116, 3:121, 3:127
Genitals, human, 3:142–143, 3:238–239, 3:240
Germs, 3:244, 3:283–284, 3:288, 3:290, 3:396
Goiters, 1:*123*
Hartnup disease, 3:15
Hearing, 2:318
Hearts, 2:324
Hemophilia, 3:115–116, 3:241–242
Histamines, 3:266–267
HIV (human immunodeficiency virus), 3:250, 3:258–261, 3:259, 3:*259*
Hospitals, 3:154
Human eggs, 3:143
Huntington disease, 3:128
Hydrochloric acid, 1:231, 1:256
Hydrogen sulfide, 3:54
Hypersomnia, 3:310
Immune system, **3:262–269**
Immunotherapy, 3:239
In vitro fertilization, 3:144, 3:*144*
Indigestion, 3:48
Infection, **3:283–291**
Infectious diseases, 3:230, 3:240, **3:244–252,** 3:264, 3:278, 3:396

Influenza, 3:60, 3:249–250, 3:287
Inner ear, 2:317–318
Insulin, 3:120, 3:242–243
Intestinal gas, 3:54
Iodine, 1:*123,* 1:234, 1:236
Iron lungs, 3:287
Jet lag, 3:310–311
Kaposi's sarcoma, 3:258, 3:*259*
Ketoacidosis, 3:243
Ketones, 1:369
Kidney dialysis, 1:*350,* 1:351
Kleine-Levin syndrome, 3:310
Kwashiorkor, 3:85
Labor (birth), 3:153
Lactic acid, 3:59
Lactose intolerance, 3:27
Large intestine, 3:47
Leprosy, 3:248–249, 3:*249*
Lipids, 3:19, 3:35, 3:44–45, 3:80
Lithium, 1:165
Liver, human, 3:*79,* 3:91–92
Loa loa, 3:279
Low-density lipoproteins, 3:36–37
LSD (lysergic acid diethylamide), 3:307
Lung cancer, 3:62
Lungs, 3:56–58, 3:*59*
Lupus (systemic lupus erythematosus), 3:268
Lymph nodes, 3:263
Lymphocytes, 3:255, 3:*263,* 3:263–264
Mad cow disease, 3:233
Malaria, 3:249, 3:276–277
Male reproductive system, 3:142–143
Malnutrition, 3:82–86, 3:89
Manic depression, 1:165
Marfan syndrome, 3:114–115
Marrow (bone), 3:263, 3:*263*
Melanin, 3:130–131, 3:173
Melatonin, 3:307, 3:314–315
Menstruation, 3:286, 3:313
Mental development, 3:334
Mercury thermometers, 1:16, 1:189, 2:250–251
Metabolic enzymes, 3:27
Metabolism, **3:33–43**
Microscopes, 3:*288*
Middle ear, 2:317
Midgets, 3:129
Midwives, 3:153–154
Miscarriage, 3:152–153
Mothers and babies, 3:73
Narcolepsy, 3:309
Native Americans, 4:344–345
Nervous system, 3:295–297, 3:*296*
Neurological disorders, 3:302
Niacin, 3:15, 3:95
Noninfectious diseases, **3:236–243**
Noses, 2:*217*
Nursing mothers, 3:73
Obstetricians, 3:154
Organ transplants, 3:262–263
Osteomalacia, 3:91
Overweight Americans, 3:10, 3:37, 3:81, 3:*82,* 3:85–86
Oxytocin, 3:153
Pancreas, human, 3:47
Parasites, 3:275–282
Pathogens, 3:245, 3:255, 3:262, 3:285–286
Pellagra, 3:15, 3:95
Penicillin, 3:290
Peptide linkage, 3:13, 3:18
Pheromones, 3:303–304
Phosphorus, 3:91
Physicians, 3:153–154, 3:238–239
Pineal gland, 3:306–307
Placenta, 3:153
Plagues, 1:360, 3:230, 3:*231,* 3:246–248
Plasma, 1:343–344, 2:14, 2:210, 3:47
Pneumonia, 3:60, 3:62, 3:287
Poliomyelitis, 3:257–258, 3:*287*
Pollution, 3:240–241
Pregnancy, 2:324, **3:151–157**
Proteins, 3:10, 3:13, 3:18–19, 3:79–82
Rabies, 3:257
Recommended daily allowances (RDA), 1:125–126
Red blood cells, 1:351, 3:*263,* 3:276–277
Respiratory disorders, 3:60, 3:62
Retroviruses, 3:287
Rickets, 3:*90,* 3:91
Scurvy, 3:93
Senses, 2:318, 3:295–305
Sickle-cell anemia, 3:*14,* 3:15–16
Silicone implants, 4:161, 4:*161*
Skin, 3:130, 3:244–245, 3:248, 3:262
Sleep cycles, 3:310
Sleep disorders, 3:309–311
Smallpox, 3:230–231, 3:252, 3:256, 3:*257, 3:396*
Soot, 3:173, 3:240, 3:*240*
Sperm cells, 3:100, 3:132, 3:136, 3:142–143
Starches, 3:7
Stethoscopes, 2:146–147
Stomach, human, 3:46–48, 3:*49*
Sugars, 3:9–10, 3:19, 3:34
Sulfa drugs, 3:3–4, 3:290
Sunlight, 3:91
Surgical silicone implants, 4:*161*
Taste, 3:301
Taste buds, 3:298–300
Thermometers, 1:14, 1:16–17, 2:*238,* 2:241–244
Thiamine (vitamin B1), 3:92, 3:95
Thymus gland, 3:263
Tobacco use, 3:240, 3:301–302
Tongue (human), 3:299–301
Trace elements, 1:123–126, 3:78
Trichinosis, 3:278

Tuberculosis, 3:60, 3:248–249
Tumors, 3:238
Twins, 3:115
Typhoid fever, 3:251
Ulcers, 3:48–49, 3:*49*
Ultrasonics, 2:324
Undercooked meat, 3:277–278, 3:303
Urine, 1:*200*
Uterus, 3:152–153
Vaccinations, 3:258
Vegetables, 3:93
Viruses, 3:60, 3:250–251, 3:259–261, 3:285–287
Vitamin A, 3:80, 3:88–90
Vitamin B1 (thiamine), 3:92, 3:95
Vitamin B2, 3:92
Vitamin B6, 3:92
Vitamin B12, 3:92, 3:268–269
Vitamin C, 3:*92,* 3:93
Vitamin D, 3:*90,* 3:90–91
Vitamin E, 3:91
Vitamin K, 3:91–92
Vitamins, 3:45, 3:80–81, **3:87–96**
X-rays, 2:298, 2:350, 2:352–353
Zinc, 1:*154,* 1:188–189

MILITARY

Afghanistan, 4:263
Biological warfare, 3:251–252
Cruise missiles, 2:82–83
Eavesdropping devices, 2:325
Explosives, 3:351–352, 4:*333*
Guided missiles, 2:82–85
Gunpowder, 1:292
Hiroshima bombardment (1945), 1:72
Incendiary devices, 1:175–176
Kevlar, 1:*375*
Landsat (satellite program), 4:57, 4:59
Lasers, 2:361–362
Listening devices, 2:*322*
Manhattan Project, 1:72, 1:97, 1:199–200, 2:177
Mountain warfare, 4:263
Nagasaki bombardment (1945), 1:72, 3:*104*
Nuclear bombs, 1:72, 1:292–293
Radar ranges, 2:348
Remote sensing, 4:53–54
Rockets, 2:31, 2:33, 2:39
Sirenians, 3:221–222
Strategic Defense Initiative (SDI), 2:178–179
Sumer, 2:162

MUSIC

Music, 2:274, 2:276
Acoustics, 2:311–314
Amplification, 2:315
Cassette tapes, 2:336–337
Decibels, 2:314
Electromagnetic sound devices, 2:336
Intervals, 2:274, 2:276
Magnetic recording devices, 2:*332,* 2:*333,* 2:336–337
Magnetic sound devices, 2:336
Magnetic tape, 2:336–337
Metronomes, 2:267, 2:274
Microphones, 2:336
Middle C, 2:*273,* 2:274
Musical instruments, 2:314
Octaves, 2:274, 2:276
Pianos, 2:*273,* 2:*313*
Recording devices, 2:*332,* 2:*333,* 2:336–337
Sound production, 2:314–315
Sound reception, 2:316–318
Tuning forks, 2:*287,* 2:289–290

NAVIGATION

Navigation, 2:334
Animals, **3:335–341**
Cartography, 4:45, 4:46
Compasses, magnetic, 2:334–335, 4:180
Geography, **4:44–52**
Global positioning system, 4:52, 4:*54*
Greenwich meridian, 2:*5*
Inertial navigation systems, 2:64
Latitude and longitude, 2:7–8
Lighthouses, 2:297
Longitude, 2:*5,* 4:51–52
Magnetic compasses, 2:334–335, 4:180
Magnetic fields, 2:332, 4:*178*
Maps, **4:44–52**
Mercator projections, 4:*46*
Prime meridian, 2:*5*
Water clocks, 2:100–101, 2:163

SPORTS AND HOBBIES

Aqualungs, 2:124
Baseball, 2:*40,* 2:44, 2:80–82, 2:117–119
Basketball, 3:261
Bicycle aerodynamics, 2:109
Bicycles, 2:109
Billiard balls, 2:*38,* 2:40–41
Boomerangs, 2:107, 2:115–116
Bouncing balls and energy, 2:175–176
Bungee jumping, 2:*265,* 2:267
Centripetal force, **2:45–50,** 2:*46*
Cheerleaders, 2:140, 2:*141*
Curve balls, 2:80–82, 2:117–119
Decompression, 1:*50,* 2:123–124
Delta wing kites, 2:108

Diving bells, 2:123
Fireworks, 1:*174*
Fish finders, 2:*321*
Fishing rods, 2:161–162
Fishing sonar, 2:*321*
Frisbees, 2:33
Golf, 2:*81,* 2:82
Handlebars (bicycles), 2:109
Helmets, bicycle, 2:109
Hockey, 2:54–55
Human cannonballs, 2:*70*
Ice fishing, 2:*247*
Ice skating, 2:27, 2:33
Karate chops, 2:140
Kite aerodynamics, 2:107–108
Kites, 2:107–108, 2:*114,* 2:116
Knuckle balls, 2:81–82
Mexico City Olympics (1968), 2:146
Mountain climbing, 1:*298*
Olympics (Mexico City, 1968), 2:146
Optical illusions, 2:359
Paper airplanes, 2:108
Parafoils, 2:108
Projectile motion, **2:78–85**
Racing cars, 2:109–110
Rapture of the deep, 2:123–124
Rockets, 2:31, 2:33, 2:82–85
Roller coasters, 2:46–47, 2:*47,* 2:49–50
Sand castles, 4:265–266, 4:274
Scuba diving, 1:*50,* 1:54, 1:242, 2:124
Seesaws, 2:86–89
Self-contained underwater breathing apparatus, 2:124
Skating, 2:27, 2:*29,* 2:33
Skis, 2:140–141
Skydiving, 2:*39,* 2:43–44
Sledges, 2:162
Snowballs, 2:228
Snowshoes, 2:140–141
Sonar fishing, 2:*321*
Spinning tops, 2:33
Swimmers, 2:122
Swings, 2:263–264, 2:*279,* 2:281
Trampolines, 2:*264*
Underwater diving, 1:*50,* 1:54, 1:242, 2:124
Water balloons, 2:44
Weightlifting, 3:308
Wheels, bicycle, 2:109
Wings, 2:108
Yachts, 4:27–28

TEXTILES

Carbon polymers, 1:372
Cellulose, 3:7–8
Cotton, 1:*373*
Indigo, 2:355
Nylon, 1:*282,* 1:366, 1:378
Polyester, 1:378–380

TRANSPORTATION

Airplanes, 2:128
Airports, 3:312
Axles, 2:162–164
Ballast, 2:122
Bicycles, 2:109
Boat wakes, 2:*288*
Car aerodynamics, 2:109–111
Carburetors, 2:117
Carriages, horsedrawn, 2:163
Cartography, 4:45, 4:46
Challenger space shuttle explosion (1986), 1:257, 1:259, 1:294
Coaches, horsedrawn, 2:163
Displacement of ships, 2:122
Doppler radar, 2:*303,* 2:305, 4:403–404
Highways, 3:380
Interstate-285 (Atlanta, GA), 2:45–46
Lighthouses, 2:297
Liquefied natural gas (LNG), 2:200–201
Liquefied petroleum gas (LPG), 2:200–201
Mach numbers, 2:106–107, 2:305
MAGLEV trains, 2:337–339
Magnetic compasses, 2:334–335, 4:180
Magnetic levitation trains, 2:337–339
Northeast Passage, 3:88
Propellers, 2:106, 2:116, 2:166–167
Radar, 2:348–349
Railroad tracks, 2:*246,* 2:250
Roads, 2:48
Sahara Desert, 4:*307*
Sailors, 3:93
Salt caravans, 1:*168*
Ships, 2:22, 2:24–25, 2:121–122, 2:137, 2:144
Shock absorbers, 2:266–267
Sonar, 2:*320*
Space shuttles, 2:*60,* 2:85
Spokes (wheels), 2:162
Stagecoaches, 2:163
Steamships, 2:121–122
Submarines, 2:122–123, 2:*320,* 2:325
Titanic (ship), 2:125
Trains and magnetic levitation, 2:337–339
Trieste (bathyscaphe), 2:124–125
Trucks, 2:110–111
Unmanned underwater vessels, 2:124–125
Wakes, boat, 2:*288,* 2:289
Whirlpools, 4:*363*
Yachts, 4:27–28

WEAPONS

Biological warfare, 3:251–252
Bombs, 1:71–72, 1:93, 2:230–231
Bullets, 1:*375,* 2:*79,* 2:80
Cruise missiles, 2:82–83
Crystal lasers, 2:369
Guided missles, 2:82–85
Gunpowder, 1:292
Heavy water, 1:96
Hiroshima bombardment (1945), 1:72
Hydrogen bombs, 1:*93,* 1:97, 1:255, 2:177–179
Incendiary devices, 1:175–176
Intercontinental ballistic missiles (ICBMs), 2:82
Manhattan Project, 1:72, 1:97, 1:199–200, 2:177
Muskets, 2:80
Nuclear weapons, 1:72, 1:98, 1:292–293, 2:177–179, 3:103, 3:*104*
Nuclear weapons testing, 1:177, 4:234
Patriot missiles, 2:*83*
Projectile motion, 2:78–80, 2:81–82
Rifles, 2:*28,* 2:31, 2:38, 2:80
Rockets, 2:31, 2:33, 2:82–85, 2:85
Stinger missiles, 2:83
Surface-to-air missiles, 2:83
V-2 rockets, 2:82
Wars, 1:71–72, 1:93, 1:175–176, 1:231

WEATHER

Weather, 4:395–404
Acid rain, 4:*318,* 4:321–322
Air-mass storms, 4:398–399
Air pressure, 2:183, 4:396–398, 4:399
Altocumulus clouds, 4:391, 4:*391*
Altostratus clouds, 4:391
Atmosphere, 4:396–397, 4:405–407
Atmospheric pressure, 1:39, 2:239, 2:241
Atmospheric water, **4:387–394**
Aurora borealis, 4:*79,* 4:79–80
Barometers, 1:50–51, 2:141–142
Biological weathering, 4:265, 4:274
Central Park (New York, NY) microclimate, 4:410
Cirrus, cirrocumulus, and cirrostratus clouds, 4:391
Climate, 3:353, 4:260, 4:405–407, **4:405–412**, 4:407, 4:409–411
Climate changes, 4:410–411
Climatology, 4:407
Cloud seeding, 4:404
Clouds, 4:390–392, 4:*391,* 4:391–392, 4:404
Cold climate, 3:374, 3:*394,* 3:394–395
Condensation, 2:209–210, 4:372
Corrosion, 1:294
Crosscurrent exchange, 3:58
Cumulonimbus clouds, 4:*187,* 4:187–188, 4:391–392
Cumulous clouds, 4:391
Cyclones, 4:400–402, 4:*401*
Desertification, 4:309–310
Doppler radar, 2:*303,* 2:305, 4:403–404
Drafts (air currents), 2:98
Drizzle, 4:392
Drought, 4:*287*
Dry ice, 1:248, 4:*402*
Dust bowls, 3:352, 4:270, 4:286, 4:*303,* 4:304–305
Dust devils, 4:*269*
El Niño consequences, 4:28, 4:30
Electric thermometers, 1:17, 2:242–244
Erosion, 4:*284*
Evapotranspiration, 4:390
Greenhouse effect, 4:355–356
Gulf Stream, 4:364
Hail, 4:392, 4:399, 4:*399*
Heaviside layer, 2:346
High-level clouds, 4:391
Hurricane Andrew (1989), 4:400–401
Hurricane Hugo (1989), 4:400
Ice ages, 4:381–384, 4:411–412
Ice caps, 4:379–380
Ice-core samples, 4:379
Kennelly-Heaviside layer, 2:346
Krakatau (Indonesia), 4:31
Lightning, 4:398
Litmus paper, 1:314
Little Ice Age (1250-1850), 4:384
Low-level clouds, 4:391
Mercury barometers, 2:141
Mercury thermometers, 1:16, 1:189, 2:250–251
Meteorological radar, 2:*303,* 2:305
Meteorology, 4:402–404, 4:406–407
Microclimates, 4:*407,* 4:407–409, 4:*410*
Mid-level clouds, 4:391
Mirages, 2:359
Mount Pinatubo eruption (1991), 4:409–410
Mountain rain shadows, 4:260
National Weather Service, 4:402–403
New York (NY) microclimate, 4:410, 4:*410*
Nimbostratus clouds, 4:391–392
Northern latitudes, 3:310
Ocean currents, 4:363–364
Philippine microclimate, 4:407–408
Precipitation, 3:358, 3:374–375, 4:372, **4:387–394**
Rain, 4:279, 4:392
Rain clouds, 4:391–392
Rain shadows, 4:260
Rainbows, 2:358–359, 4:78
Seasons, 3:313–315
Sky, 2:358
Sleet, 4:392
Snow, 4:377, 4:392
Snowflakes, 4:*392*
Solar wind, 4:80
Stratocumulus clouds, 4:391

Stratosphere, 2:127
Stratus clouds, 4:391
Sulfur, 4:*318,* 4:321–322
Sun, 4:384, 4:396, 4:409–410
Thermometers, 1:14, 1:16–17, 2:*238,* 2:241–244
Thunderstorms, 4:*187,* 4:187–188, 4:391–392, 4:398–399
Tides, 4:84, 4:364
Tornado Alley (U.S.), 4:400
Tornadoes, 4:399–400
Trees, 3:*362*
Troposphere, 4:405–406
Van Allen belts, 4:80
Volcanoes, 4:30–31, 4:409–410
Water, 3:347–348, 3:358, **4:387–394**
Whirlpools, 4:*363*
Wind, 4:188, 4:396–398

CUMULATIVE GENERAL SUBJECT INDEX

This index contains items from volumes 1-4 of the series.
Boldface type indicates main entry volume and page numbers.
Italic type indicates photo and illustration volume and page numbers.

A

Aardvarks, 3:222
Abegg, Richard, 1:103–104, 1:113, 1:268, 4:131
Abney, William, 2:349–350
Aborigines, Australian, 2:107
Abrasive minerals, 4:137
Absolute dating
  amino acid racimization, 3:17, 4:96–97, 4:119–120
  carbon ratio dating, 1:98, 1:250–251, 4:97–98, 4:120
  potassium-argon dating, 1:*238,* 4:98
  uranium series dating, 3:172, 4:98
Absolute temperature scale. *See* Kelvin temperature scale
Absolute zero
  Carnot's engine, 2:222
  heat engines, 2:232
  Kelvin scale, 2:241
  solids, 2:208
  third law of thermodynamics, 2:223, 4:195
Absorption spectrums, 2:366–367
Acceleration
  centripetal force, 2:46–47
  gravity, 2:19, 2:71
  laws of motion, 2:18–20
  roller coasters, 2:49–50
  second law of motion, 2:65, 4:171
  speed and velocity, 2:17–18
Accelerometers, 2:46
Accidents as cause of death, 3:231
Acheson, Edward G., 4:137
Acid-base reactions, 1:285, **1:319–326,** 1:324*t*–325*t*
Acid rain, 4:*318,* 4:321–322
Acid reflux, 3:48
Acids, 1:278, **1:310–318,** 1:*312,* 1:316*t*–317*t*
Acne, 3:286
Acoustics, **2:311–318,** 2:316*t*–317*t*
  classical physics, 2:20
  diffraction, 2:294–295
  Doppler effect, 2:303–305
  interference, 2:289–290
  properties, 2:256
  resonance, 2:283
  ultrasonics, 2:319–321
  See also Sound; Sound waves
Acquired characteristics, 3:165
Actinides, 1:156, **1:196–204,** 1:202*t*–203*t*
  electron configuration, 1:136
  orbital patterns, 1:146, 1:186
Actinium, 1:198
Active sites (enzymes), 3:25
ADA (American Dietetic Association), 3:96
Adenosine diphosphate (ADP), 3:34
Adenosine triphosphate (ATP), 3:34, 3:56
Adrenaline, 3:267–268
Advanced Cell Technology (Worcester, MA), 3:123
Adventures of Huckleberry Finn (Twain), 4:64
Aerial photography
  Colorado River delta, 4:*56*
  geography, 4:47–48
  history, 4:53–54
Aerobic decay, 1:360
Aerodynamics, **2:102–111,** 2:110*t*
  Bernoulli's principle, 2:98
  bullets, 2:*79*
  See also Air resistance; Airflow; Dynamics
Aeronautics industry, 1:*172*
Aerosol cans, 1:55, 2:187–188
Aerostat blimp, 2:*127*
Afghanistan and mountain warfare, 4:263
Africa and AIDS epidemic, 3:250
African black rhinoceros, 3:386, 3:*387*
African trypanosomiasis, 3:276
Agricola, Georgius
  economic geology, 4:154–155
  mineral classification, 4:133
  mineralogy, 4:39

Agriculture
biomes, 3:380
bred crop species, 3:387
ecosystems, 4:343–344
flooding, 4:365–366
history, 3:395–396
nitrogen cycle, 4:338
slash-and-burn, 3:350
soil, 4:300
soil conservation, 3:352, 4:304–305
See also Crops
AIDS (Acquired immunodeficiency syndrome), 3:245, 3:250, 3:258–261, 3:*259*
Air conditioners, 2:219–220
Air-mass storms, 4:398–399
Air pressure
fluid pressure, 2:142
human body, 2:145–146
measurement, 2:183
Mount Everest, 2:*142*
tornadoes, 4:399
weather, 4:396–398
Air resistance
conservation of angular momentum, 2:27
gravity and acceleration, 2:20, 2:74–75
projectile motion, 2:78–80
See also Friction; Terminal velocity
Airbags, 1:56, 1:58–59
gas laws, 2:189–190
linear momentum, 2:43
Airflow, 2:144
See also Aerodynamics; Laminar flow
Airfoils
airplanes, 2:105–107
Bernoulli's principle, 2:97–98, 2:116
fluid pressure, 2:144
Airplanes
air pressure, 2:146
Bernoulli's principle, 2:116
center of gravity, 2:137
flight, 2:105–107
jet lag, 3:310–311
paper airplanes, 2:108
transportation, 2:128
Airports, 3:312
Airships, 1:*254,* 1:257, 2:126–129
See also Balloons; Blimps; Dirigibles; Hot-air balloons
Alaska
earthquakes, 4:235
ecosystems, 3:*404,* 3:405
Albatrosses, 3:338
Albertus Magnus, 3:196
Albinism, 3:*130,* 3:130–131
Alchemy, 1:112, 1:224
Alcohol, 1:369
cancer, 3:240
distillation, 1:356–357
fermentation process, 3:27–28
thermometric medium, 2:242
use and abuse, 3:59
Aldehydes, 1:369
Aldrin, Buzz, 1:*24*
Alexis (son of Czar Nicholas II), 3:*242*
Alfred A. Murrah Federal Building bombing (1995), 4:*333*
Algorithms, 3:193
Al-hasen (Arab physicist), 2:342, 2:354
Alien (motion picture), 2:315–316
Alighieri, Dante, 4:215
Alkali metals, 1:153, **1:162–170,** 1:169*t*
Alkalies, 1:310–311, 1:319
Alkaline earth metals, 1:153–154, **1:171–180,** 1:*174,* 1:178*t*–179*t*
Alkanes, 1:367–368
Alkenes, 1:368
Alkynes, 1:368
Alleles, 3:112
Allergies, 3:60, 3:264–268, 3:*265,* 3:364–365
Allopatric species, 3:217
Allotropes, carbon, 1:245–247
Alloy metals, 1:192
Alloys, 1:334, 1:336
Alluvial soil, 3:351
Alpha-fetoprotein screening, 3:156
Alpine glaciers, 4:378
Alternative energy sources, 4:202, 4:206
Alternative treatments for cancer, 3:239
Altitude and forest ecology, 3:362–363
See also Tree lines
Altocumulus clouds, 4:391, 4:*391*
Altostratus clouds, 4:391
Aluminum, 1:*152,* 1:157
atomic structure, 1:101
covering of World Trade Center (New York, NY), 1:*153*
human health, 1:124–125
ions and ionization, 1:121
oxidation-reduction reactions, 1:295–296
Aluminum hydroxide, 1:315
Alzheimer's disease, 3:*233,* 3:233–235
AM radio broadcasts, 2:276–277, 2:345–346
Amazon River valley (Brazil) deforestation, 3:365, 3:*366,* 4:57, 4:59
American chestnut trees, 3:394
American diet, 3:49–50, 3:79
overweight Americans, 3:10, 3:37, 3:81, 3:*82,* 3:85–86
recommended daily allowances (RDA), 1:125–126
American Dietetic Association (ADA), 3:96
American elm, 3:210

Americium, 1:201–202
Amino acid racimization, 3:17, 4:96–97, 4:119–120
Amino acids, **3:11–17,** 3:16*t*
  enzymes, 3:24
  proteins, 3:18–19, 3:79–80
  racimization, 4:96–97, 4:119–120
Ammonia
  in fertilizers, 3:351
  nitrogen cycle, 4:335
Ammonification, 4:338
Ammonium, 4:335
Ammonium nitrate, 3:351–352, 4:*333*
Amniocentesis, 3:156
Amoebic dysentery, 3:276
Amorphous carbon, 1:246–247, 4:326
Amorphous matter, 2:210
Amoxicillin, 3:290–291
Ampère, André Marie, 2:341, 4:178
Amplification, electronic, 2:315
Amplitude
  acoustics, 2:313–314
  Doppler effect, 2:301–302
  electromagnetism, 2:344
  frequency, 2:273
  modulation of radio waves, 2:260–261
  oscillations, 2:264
  resonance, 2:279
  ultrasonics, 2:320
  waves, 2:257
Anabolism, 3:33, 3:34–35
Anaerobic decay, 1:360
Anaerobic respiration, 3:58–59
Anaphylactic shock, 3:265, 3:267–268
Ancestral record and evolution, 3:170–171
Andes Mountains (Peru), 2:146
Andrews, Roy Chapman, 4:17
Anemia, 3:268–269
Anesthetics and childbirth, 3:154
Angiosperms, 3:173–174, 3:*362,* 3:*364,* 3:364–365
  gymnosperms vs., 4:347–349
  reproduction, 3:138, 3:140–141
Angle of attack, 2:106
Angle of repose, 4:265–266, 4:274
Angstroms in atomic measurements, 1:76–77
Angular momentum
  conservation, 2:27, 2:30, 2:33
  projectile motion, 2:80
  torque, 2:89
  See also Conservation of angular momentum; Momentum
Angular unconformities (geography), 4:112–113
Animals
  behavior, 3:321–326
  biomes, 3:375
  carbon dioxide, 4:327
  chemoreception, 3:297–298
  cloning, 3:123
  domestication, 4:343–344
  evidence of evolution, 3:169–171
  hibernation, 3:40–43
  human intelligence vs., 3:167–168
  instinct and learning, 3:327–334
  kingdom animalia, 3:198, 3:205, 3:206
  mating rituals, 3:145–147
  migration, 3:338–341
  natural selection, 3:163–165
  pregnancy and birth, 3:151–153
  presence of proteins, 3:20–21, 3:23
  respiration, 3:58, 4:329–330
  selective breeding, 3:128, 3:169
  sense of smell, 3:303
  shedding (fur or skin), 3:313, 3:*313*
  symbiotic relationships, 3:386–387
  transpiration, 3:355, 3:358, 4:389–390
  ultrasonics, 2:323–324
  See also Mammals; *specific species*
Anion resins, 1:106
Anions, 1:101–102
  aluminum, 1:121
  naming system, 1:277
  nonmetals, 1:103
Annelids
  asexual reproduction, 3:*138*
  detritivores, 3:349
  respiration, 3:57, 3:*57*
Anorexia nervosa, 3:38–39
Antacids, 1:322–323, 3:48
Antarctica, 4:*377*
  glaciology, 4:378–380
  midnight sun, 3:310
Anteaters, 3:*223,* 3:223–224
Anthrax, 3:*250,* 3:251–252
Anthropogenic biomes, 3:378–380
Anthropoidea, 3:220–221, 3:274–275
Antibiotics
  amino acids in, 3:13
  bacterial resistance to, 3:165, 3:290–291
  discovery, 3:290
Antibodies, 3:122–123, 3:263–264
Antiferromagnetism, 2:332, 2:334
  See also Magnetism
Antihistamines, 3:267
Antimony, 1:226
Antioxidants, 1:294, 3:91
Antipater of Thessalonica, 2:163
Ants, 3:*349,* 3:349–350, 3:386, 3:388
Apatosaurus, 3:184
Aphids, 3:388
Apis mellifera scutellata, 3:211
Apnea, 3:310
Apple tree stomata, 4:*388*
Appliances, 1:*374*

Aqualung, 2:124
Aquatic animals
behavior, 3:*321*
bioaccumulation, 3:72–73
echolocation, 3:340–341
endangered species, 3:208
evolutionary history, 3:195, 3:204–205, 3:221–222
food webs, 3:77, 3:376–377
migration, 3:336
mussels, 3:211
reproduction, 3:143–144
respiration, 3:57
taxonomy, 3:*199*
See also Fish; Oceans
Aquatic biomes, 3:370
Aqueducts, 4:91–92
Aqueous solutions, 1:284, 1:320, 1:343–344
Aquifers, 3:347
Arabic language in chemical symbols, 1:133
Arabic numerals, 1:4
Arachnida (class), 3:275
Archaean eon, 4:116
Archaeological geology, 4:19
Arches, 4:14, 4:*15*
Archimedes (scientist)
buoyancy, 2:24, 2:96–97, 2:120
fluid pressure, 2:144
machines, 2:158
pulleys, 2:164
Archimedes screws, 2:166
Archimedes (ship), 2:166
Archimedes's principle, 2:120
Arco Sag River (ship), 2:*22*
Arctic fox, 3:*394*
Arctic Ocean, 3:88
Arctic tern, 3:338
Arduino, Giovanni, 4:108
Argon, 1:241
Aristarchus of Samos, 4:64
Aristotelian physics, 2:14–16, 4:7–9
development, 2:14–15
Earth's spheres, 4:25
flaws, 2:15–16
four elements, 2:15, 2:69–70
gravity, 2:69–70
motion, 2:14–16, 2:18
theory of impetus, 2:61
See also Greek thought
Aristotle, 1:67–68, 4:*4*
causation, 4:3–5
founder of taxonomy, 3:*192,* 3:196–197, 3:222
See also Aristotelian physics
Arkansas River, 4:*372*
Armstrong, Edwin H., 2:346
Armstrong, Neil, 1:*24*
Aromatic hydrocarbons, 1:368
Arrhenius, Svante, 1:*311*
Arrhenius's acid-base theory, 1:311–312, 1:320
Arsenic, 1:225–226, 3:78
Arteries. *See* Circulatory system
Arthropoda (phylum), 3:275, 3:279–282
See also Insects
Artichokes, 3:6
Artificial elements, 1:195, 1:*198*
Artificial polymers. *See* Synthetic polymers
Artificial satellites. *See* Satellites
Artiodactyls, 3:223
Asbestos, 4:139
Ascaris lumbricoides, 3:278
Ascorbic acid. *See* Vitamin C
Asexual reproduction, 3:135, 3:136–138, 3:*138,* 3:285
See also Reproduction
Aspect ratio of paper airplanes, 2:108
Astatine, 1:236
Astbury, William Thomas, 2:297
Asteroids
catastrophism, 4:92
mass extinctions, 3:185–186, 3:*186,* 4:126–127
Meteor Crater (AZ), 4:*91*
See also Meteorites
Asthenosphere
convection, 4:188
structure, 4:212–214
Astronauts
sleep cycles, 3:310
space walks, 4:*215*
Astronomical clocks, 2:267
Astronomical units, 4:75
Astronomy
gamma rays, 2:353
infrared imaging, 2:350
magnetism, 2:335
Newton's three laws of motion, 2:18–20
relative motion, 2:9–10
science and religion, 4:9, 4:63–64
specific gravity, 2:26
ultraviolet imaging, 2:350
See also Cosmology; Planetary science
Atheism, 3:167, 4:90
Athena (goddess), 3:138
Athens (ancient Greece), 3:287
Atherosclerosis, 3:*36*
Atlanta (GA)
geomorphology, 4:18
microclimate, 4:410
traffic, 2:45–46
Atlantis (mythical continent), 4:6
Atmosphere (Earth's)
atmospheric sciences, 4:43
carbon cycle, 4:328–330
climate, 4:405–407

compared to water, 1:49
composition, 4:405
deforestation, 4:355–356
dust following massive asteroid strike, 3:185
early Earth, 3:178
elements of, 3:346
energy, 4:198
geoscience, 4:26
plant evolution, 4:293
role in biosphere, 3:347–348
subsidence, 4:188, 4:190–191
water, **4:387–394**
weather, 4:396–397
wind, 4:396–398
See also Earth sciences
Atmosphere (unit of measure), 2:141–142
Atmospheric pressure, 1:39
boiling, 2:209
temperature, 2:239, 2:241
Atomic bombs, 2:177–179
fluorine, 1:232–233
nuclear fission, 1:71–72, 1:93
radioactive fallout, 3:103, 3:*104*
Atomic bonding
carbon, 1:244–245
octet rule, 1:103–104
Atomic Energy Commission (AEC), 3:103
Atomic hypothesis. *See* Atomic theory
Atomic mass, **1:76–83,** 1:82*t*–83*t,* 1:128, 1:130–131
Atomic mass units (amu), 1:25–26, 1:77
calibration, 1:81
hydrogen standard, 1:131–132
molar mass, 1:27
Atomic models, 1:64–65
Atomic numbers, 1:65, 1:71, 1:80, 4:74
element's energy, 1:130
isotopes, 1:95
Atomic size
main-group elements, 1:*141*
periodic table of elements, 1:136, 1:138
Atomic structure, 1:64–65, 1:84–85
bonding, 1:267
carbon, 1:363–364
electrons, 1:86–87
elements, 1:119–120
silicon, 1:363–364
Atomic theory, 1:34, 1:63, 1:*66,* 1:68–74, 1:128
Berzelius, Jons, 1:79
Dalton, John, 1:264–265
development, 4:7–8
discovery, 2:195
origins in Greece, 1:127, 1:263, 2:14
proof of theories, 3:166
structure of matter, 2:205
Atomic weight. *See* Atomic mass
Atomizers and Bernoulli's principle, 2:116–117
Atoms, 1:34–35, 1:36, **1:63–75,** 1:74*t*–75*t,* 1:*86*
Avogadro's number, 1:53
chemical equations, 1:283–284
electromagnetic force, 2:207
excitement, 2:366–367
lasers, 2:361
magnetism, 2:331, 4:179
minerals, 4:130–131
molecules, 2:192
structure, 4:73–74
ATP (adenosine triphosphate), 3:34, 3:56
Attention (brain function), 3:307
Aurora australis, 4:*79,* 4:79–80
Aurora borealis, 4:*79,* 4:79–80
Australia
Aborigines and boomerangs, 2:107
marsupials, 3:219
Australopithecus, 3:215–216
Automobile industry, 1:176
Automobiles. *See* Cars
Automotive engine torque, 2:90
Autosomes, 3:111–112
Autotrophs, 3:77, 3:87–88
Avalanches, 4:*275*
See also Flow (geology)
Average atomic mass, 1:77, 1:131
Avery, Oswald, 3:111, 3:117
Avogadro, Amedeo, 1:53
atomic theory, 1:68–69
molecular theory, 1:79, 1:112, 1:265, 2:205
Avogadro's law, 2:184–185
Avogadro's number, 1:26–27, 1:53, 1:78, 2:184–185, 2:193–194, 2:205–206
atomic mass units, 1:131
molecule measurement, 1:36
Axes
frame of reference, 2:6
statics and equilibrium, 2:134
tension calculations, 2:135–136
See also Cartesian system; Graphs
Axles, 2:162–164

B

B cells, 3:255, 3:263–264
B vitamins, 3:92
Bachelet, Emile, 2:338
Bacillus anthracis, 3:251
Bacteria
anaerobic, 3:58
antibiotics and, 3:165
decomposers, 3:361
in digestive system, 3:*51,* 3:51–54
infection, 3:284–285, 3:286
infectious diseases, 3:245, 3:248, 3:250, 3:252,

3:264
origin of life, 3:179
ulcers, 3:48–49, 3:*49*
See also Germs
Bags, potato chip, 2:188
Baillie, Mike, 4:30–31
Bain, Alexander, 2:267–268
Baker, Howard, 4:220
Baking soda, 1:315–317, 3:48
Bakker, Robert T., 4:127–128
Balaena, 3:208
Balard, Antoine-Jérôme, 1:234
Ballast, 2:122
Ballonet, 2:127
Balloons, 2:105, 2:125–126
See also Airships; Hot-air balloons
Bangladesh and cyclones, 4:401
Banting, Frederick, 3:243
Bar magnets, 2:334, 4:*178*
See also Magnets
Barents, Willem, 3:88–89
Barium, 1:177–178
Barometers, 1:50–51, 2:141–142, 2:239
Barrel sponge (animal), 3:*199*
Barton, Otis, 2:124
Base-10 numbers, 2:7
Baseball
Bernoulli's principle, 2:117–119
linear momentum, 2:*40,* 2:44
projectile motion, 2:80–82
Bases, **1:310–318,** 1:316*t*–317*t*
alkaline earth metals, 1:154
used as antacids, 3:48
See also Acid-base reactions
Basilar membrane, 2:318
Basketballs
molecules, 2:*194*
work, 2:*171*
Bathyscaphe, 2:124–125
Bathysphere, 2:124
Bats (animals)
Doppler effect, 2:305
echolocation, 3:340
order Chiroptera, 3:220
pentadactyl limb, 3:*170*
pollinating plants, 3:141
Batteries, 1:296
lithium, 1:*163,* 1:164–165
oxidation-reduction reactions, 1:*291*
Bauer, Georg. *See* Agricola, Georgius
BBC (British Broadcasting Corp.), 3:223
Beaches
breezes, 4:188
erosion, 4:*284*
Bears, 3:*40,* 3:89
Beatles (musical group), 2:347–348
Beauty (human perception), 3:*146,* 3:147
Beavers, 3:*322*
Beavertail cactus, 3:*351*
BEC (Bose-Einstein Condensate), 1:42–43, 2:201–202, 2:211
Becquerel, Henri, 1:70
Bed load, 4:286
Bedbugs, 3:281–282
Bedrock, 4:296
Beebe, William, 2:124
Beer, 1:*340,* 1:356–357
Bees
behavior, 3:323–324
killer bees, 3:211, 3:*211*
pheromones, 3:303–304
Behavior, **3:319–326,** 3:325*t*
See also Instinct; Learning and learned behavior
Behaviorism, 3:320–321
Bends (illness), 2:123–124, 4:334
Beni Abbes Dunes (Sahara Desert), 4:*407*
Berg, Paul, 3:119
Beriberi, 3:92, 3:93–95
Berkelium, 1:203
Bernal, J. D., 2:297
Bernal chart, 2:297
Bernoulli, Daniel
fluid dynamics, 2:20
Hydrodynamica, 2:113
kinetic theory of gases, 2:195
projectile motion, 2:81–82
See also Bernoulli's principle
Bernoulli's principle, 2:97, **2:112–119,** 2:118*t*
airplanes, 2:105–106
boomerangs, 2:107
fluid mechanics, 2:97–98
fluid pressure, 2:143–144
projectile motion, 2:81–82
Bert, Paul, 2:124
Berthelot, Pierre-Eugene Marcelin, 1:18, 2:230
Berthollet, Claude Louis, 1:276, 1:330
Bertillon, Alphonse, 3:105
Beryllium, 1:175
Berzelius, Jons, 4:135
atomic theory, 1:68–69, 1:79, 1:128
catalysts, 1:306
mineral classification, 4:133
selenium, discovery of, 1:221
thorium, discovery of, 1:198
Best, Charles Herbert, 3:243
Bestiaries, 3:*196,* 3:197
Beta-carotene, 3:90
"Better living through chemistry" (marketing campaign), 1:366
Bevel gears, 2:163
Biblical geomythology, 4:5–7
Bicycles, 2:109

Biello, Stephany, 3:315
Big bang theory, 3:177, 4:71
Bighorn River (WY), 2:*96*
Bile, human, 3:47
Bilirubin, 3:51
Billiard balls, 2:*38,* 2:40–41
Binary ionic compounds, 1:277
Bingeing, 3:39
  See also Bulimia
Bioaccumulation, 3:71, 3:72–73, 3:76, 4:356–358
Biodegradable plastics, 1:377
Biodiversity, 3:365–366, 3:392
  civilization, 4:343–344
  deforestation, 4:354
  ecosystems, 4:345–346, 4:349–350
  tropical cloud forests, 4:*345*
  See also Ecosystems
Bioenergy
  biomass, 4:200–201
  fossil fuels, 4:201
Biogeochemistry, **4:313–322,** 4:319*t*–320*t,* 4:323–324
  See also Geochemistry
Biogeography, 3:400–401, 3:402–403
Biological communities, **3:391–399,** 3:397*t*–398*t,* **3:400–409**
  See also Food webs
Biological rhythms, **3:306–315,** 3:314*t*
Biological warfare, 3:251–252
Biological weathering, 4:265, 4:274
Bioluminescence, 2:367, 2:369–370
Biomagnification, 3:72–73, 4:356–358
Biomass
  bioenergy, 4:200–201
  ecosystems, 4:346
Biomes, **3:370–380,** 3:378*t*–379*t*
Biopsies in cancer diagnosis, 3:239
Biorhythms (1970's fad), 3:315
Biosphere, **3:345–359,** 3:356*t*–358*t,* 3:360
  ecology, **4:351–358**
  ecosystems, 4:341
  energy, 4:199–201
  geoscience, 4:27
Biostratigraphy, 4:106
Biotechnology, 3:119
  See also Genetic engineering
Bipolar disorder and lithium treatment, 1:165
Birds
  aerodynamics, 2:103–105
  behavior, 3:322–323, 3:324, 3:327, 3:328–329, 3:*329,* 3:330–331
  biomes, 3:*375*
  circadian cycle, 3:309
  colonization, 3:402, 3:*402,* 3:406
  endangered or extinct species, 3:208–209, 3:*209,* 3:408
  evolutionary history, 3:192
  experiments in beriberi, 3:94–95
  impact of DDT, 3:73
  mating rituals, 3:*145,* 3:146–147
  migration, 3:336–338
  parasites, 3:274, 3:330–331
  pollinating plants, 3:140–141
  respiration, 3:58
  speciation, 3:217
  symbiotic relationships, 3:384, 3:386, 3:*387*
  taxonomic keys, 3:193
  training, 3:338
  wings, 2:115
  See also specific species
Birth defects. *See* Congenital disorders
Bismuth, 1:158, 1:161
Biston betularia, 3:173
Bjerknes, Jacob, 4:402
Bjerknes, Vilhelm, 4:402
Black Death (1347-1351), 3:247–248
Black, Joseph, 1:247, 2:230
Black light. *See* Ultraviolet light
Black Sea, 4:320–321
Blackburn, Ken, 2:108
Black-throated green warblers, 3:217
Blane, Sir Gilbert, 3:93
Bleaching, 1:231–232
Blimps
  buoyancy, 2:105
  usage, 2:*127,* 2:129
  See also Airships
Block-and-tackle pulleys, 2:164
Blood
  anemia, 3:268–269
  hemoglobin, 3:19, 3:56
  hemophilia, 3:115–116, 3:241–242
  importance of bone marrow, 3:*263*
  importance of vitamin K, 3:91–92
  infections, 3:276–277
  lymphocytes, 3:263, 3:264
  oxygen diffusion in lungs, 3:56–57
  plasma, 3:47
  proteins in, 3:21
  sickle-cell anemia, 3:*14,* 3:15–16
Blood pressure
  Doppler effect, 2:305
  measurement, 2:146–147
Blood vessels, 3:*36*
Blue color of sky, 2:358
Blue-green algae, 4:*293*
Blue whales, 3:208
Boat wakes, 2:*288*
Body clock. *See* Biological rhythms
Bogs, 3:376
Bohr, Neils, 1:*65,* 1:73–74, 1:86
Boiling, 2:209
Boiling points

alkali metals, 1:163–164
alkaline earth metals, 1:173
liquids, 1:39
Boise City (OK) dust storm, 4:*303*
Boltzmann, Ludwig E., 2:196
Bomb calorimeters, 2:230–231
Bombs, 1:71–72, 1:93
See also Explosives; Nuclear weapons
Bond energy, 1:113, 1:269, 1:272
Bone marrow, 3:263, 3:*263*
Bones, 2:152
Boomerangs
aerodynamics, 2:107
Bernoulli's principle, 2:115–116
Boreal forest, 3:362, 3:371–372
Boron, 1:216
Bose, Satyendranath, 2:201–202, 2:211
Bose-Einstein Condensate, 1:42–43, 2:201–202, 2:211
Botulism, 3:252
Bouncing balls and energy, 2:175–176
Bowel movements, human, 3:50
Boyer, Herbert, 3:119
Boyle, Robert, 1:51–52, 1:68, 1:128, 2:112–113, 2:184
Boyle's law, 1:52, 2:184, 2:197, 2:249
Bragg, William Henry, 2:298
Bragg, William Lawrence, 2:298
Bragg's law, 2:298
Brain, 3:168
Alzheimer's disease, 3:*233,* 3:233–235
Creutzfeldt-Jakob disease, 3:232–233
hearing, 2:318
neurological disorders, 3:302
pineal gland, 3:306–307
processing sensory data, 3:299
Brakes (automotive), 2:55, 2:62
See also Cars
Bramah, Joseph, 2:160
Branched alkanes, 1:368
Brand, Hennig, 4:317
Brass, 1:188, 1:336
Bread, 3:28, 3:*28*
Breast-feeding, 3:73
Breathing, 2:145–146, 3:56–58
See also Respiration
Breeding. *See* Selective breeding
Breezes. *See* Wind
Breitling Orbiter 3, 2:126
Bridges
resonance, 2:*280,* 2:285
thermal expansion, 2:250
Brimstone, 4:320
Brine-curing recipes, 1:352
British Broadcasting Corp. (BBC), 3:223
British Imperial System (measurement), 1:8, 2:8–9
See also Measurements; Metric system
Broadcasting, radio, 2:276–277, 2:345–346
Brømine, 1:234
Bronchial disorders, 3:60
Bronsted-Lowry acid-base theory, 1:312–313, 1:320–321
Bronze, 1:336
Brown, Robert, 1:69, 1:332–333, 2:196, 2:206
Brownian motion, 1:69, 1:332–333, 2:195–196, 2:206
Brunhes, Bernard, 4:225, 4:228
Buchanan, Jack, 2:*54*
Buchner, Eduard, 1:306, 3:25
Buckminsterfullerene, 1:246, 1:*247,* 4:326
Buffered solutions, 1:323
Buffon, Georges-Louis Leclerc de, 4:89–90
Buhler, Rich, 4:216–218
Building materials, 1:176
Bulimia, 3:*38,* 3:38–39
Bulk modulus for elasticity, 2:149
Bulletproof vests, 1:*375*
Bullets
aerodynamics, 2:*79*
projectile motion, 2:80
Bull's horn acacia, 3:386
Bungee jumping, 2:*265,* 2:267
Buoyancy, **2:120–129**
Archimedes, 2:24
fluid mechanics, 2:96–97
fluid pressure, 2:144–145
hull displacement of ships, 2:*22,* 2:24–25
Burdock (plant), 3:389
Bureau of Standards, 1:7, 2:8
Burglar alarms, 2:335
Buridan, Jean, 2:61
Burns, Alan, 2:56
Burroughs, Edgar Rice, 3:331–332
Büsching, Anton Friedrich, 4:46
Business application. *See* Economic geology; Industrial uses
Butte County (SD), 2:137
Butterflies, 3:338, 3:388–389
Butterfly effect, 4:25
Buys-Ballot, Christopher Heinrich, 2:304
Byzantine Empire, 3:230, 3:246

C

Cabbage, 3:*26*
Cabriolets, 2:163
Cacti, 3:*351*
Cade, John, 1:165
Cadmium, 1:189
Caesar, Julius, 3:157
Cailletet, Louis Paul, 2:200
Calcite, 4:*136,* 4:138
Calcium, 1:176, 3:81, 3:91
Calcium carbonate, 3:*377,* 4:327, 4:*327*

Calderas, 4:259, 4:*259*
Calendars, 2:8
Calibration, 1:9, 1:81
California
  gold rush, 4:290
  Route 1, 4:270
  slides, 4:271–272
Californium, 1:203
Calorie (unit of measure), 2:219, 2:229
Calorimeters, 1:18–19, 2:230–231
Calorimetry, 1:18–19, 2:230–231
Calvaria major, 3:209
Cambrian period, 3:179
Camels, 3:223, 4:*307*
Camerarius, Rudolf Jakob, 3:138
Cameron, James, 2:125
Cameron, Mike, 2:125
Cancer, 3:230, 3:238–241
  lung cancer, 3:62
  mutation, 3:132
  treatment with designer proteins, 3:21
Candles
  accelerometers, 2:46
  light, 2:360–361
Candy bars, 3:10
Cannibalism, 3:396, 3:398
Canyons
  erosion, 4:270
  Neon Canyon (UT), 4:*106*
  Nicola River Canyon (British Columbia), 4:*265*
Cap rocks, 4:*159*
Capillaries (thermometers), 2:242
Car horns, 2:336
Car jacks
  fluid pressure, 2:142–143
  hydraulic presses, 2:167–168
Car lifts, 2:*160*
Caravans, 4:*307*
Carbohydrates, **3:3–10,** 3:8*t*–9*t,* 3:44, 3:*79,* 3:80–82
Carbon, **1:243–251,** 1:249*t*–250*t*
  allotropes, 4:325–326
  in amino acids, 3:11–13
  biogeochemistry, 4:315–316
  carbon bonding, 4:325
  carbon cycle, **4:323–330**
  chlorine, bonding with, 1:232
  human body composition, 1:123
  in old-growth biological communities, 3:369
  organic chemistry, 1:363–370
  organic compounds, 1:276
  origin of life, 3:178–179
  paleontology, 4:115
  percentage of biosphere, 3:348
  percentage of human body mass, 3:78
  polymers, 1:372
Carbon cycle, 4:316, **4:323–330,** 4:328*t*–329*t,* 4:355
Carbon dioxide, 1:247–248, 1:268–269, 2:200, 3:28, 3:*28,* 3:369
  carbon cycle, 4:326–329
  cloud seeding, 4:404
  dry ice, 4:*402,* 4:404
  exhaled, 3:55–56
Carbon monoxide, 1:248, 1:250, 1:301–302, 4:328–329
Carbon ratio dating, 1:98, 1:250–251, 4:97–98, 4:120
Carbonated water, 1:248
Carbonates (minerals), 4:134, 4:326–327
Carborundum, 4:137
Carboxylic acids, 1:315, 1:369
Carburetors, 2:117
Carcinogens, 3:238
Cardinals (birds), 3:327
Careers in geoscience, 4:18
Carnivores
  dinosaurs, 3:184
  food webs, 3:361, 4:200, 4:342
  order Carnivora, 3:221
Carnot, Sadi
  heat engines, 2:231–232
  thermodynamics, 2:221–222
Carnot steam engine, 2:221–222, 2:234
Carothers, Wallace, 1:376, 1:377–378
Carriages, horsedrawn, 2:163
Cars
  aerodynamics, 2:109–111
  centripetal force, 2:47–48
  collisions, 2:41–43
  friction, 2:*53,* 2:55
  gas laws, 2:188–190
  torque, 2:90
Cartesian system, 2:6, 2:*7*
  See also Axes; Graphs; Points
Cartography, 4:45, 4:46
  See also Maps
Casal, Gaspar, 3:95
Cassette tapes, 2:336–337
Castle Rock (SD), 2:137
Catabolism, 3:33, 3:34–35
Catalysts, **1:304–309,** 1:308*t*
  chemical reactions, 1:286, 1:298
  enzymes, 3:24–25
  photosynthesis, 3:5
Catalytic converters, 1:*305,* 1:307
Catastrophism
  historical geology, 4:91–92
  history, 4:39–40
Catholic Church. *See* Roman Catholic Church
Cation resins, 1:106
Cations, 1:101
  aluminum, 1:121
  metals, 1:103
  naming system, 1:277

Cats
human interaction with, 3:387
sense of smell, 3:298
taxonomy, 3:221
ultrasonics, 2:323
Cattle, 3:7–8, 3:123, 3:233
Cattle egrets, 3:*402*
Causation, 4:3–5
Caustic soda, 1:317–318
Cavendish, Henry, 4:171
Cavitation, 2:324, 2:326
Cayley, George
Bernoulli's principle, 2:115
glider flight, 2:105
kites, 2:108
CCK (Cholecystokinin), 3:10
CDC (Centers for Disease Control and Prevention), 3:258–259
CD-ROMs, 2:364
Cellular biology
amino acids, 3:14
characteristics of bacteria, 3:284–285
chromosomes and DNA, 3:99–100, 3:135
metabolism, 3:34
origins of life, 3:179
photosynthesis, 3:*4*
starches, 3:7
taxonomy, 3:198, 3:206
Cellular respiration, 1:250, 3:56, 3:*57,* 3:58–59
Celluloid, 1:377
Cellulose, 3:*6,* 3:7–8
Celsius, Anders, 2:240–241
Celsius temperature scale, 1:15, 2:240–241
Cenozoic era, 3:186, 4:108, 4:116, 4:117–118
Center of buoyancy, 2:122
Center of geography (U.S.), 2:137
Center of gravity
buoyancy, 2:122
calculations, 2:136–137
equilibrium, 2:135, 2:*136*
Center of population (U.S.), 2:137
Centers for Disease Control, 3:258–259
Centigrade scale (temperature), 2:240–241
Central Park (New York, NY) microclimate, 4:410, 4:*410*
Centrifugal force, **2:45–50,** 2:*46,* 2:*47,* 2:50*t*
See also Force
Centrifuges, 2:*46,* 2:48–49
Centripetal force, **2:45–50,** 2:*46,* 2:*47,* 2:50*t*
See also Force
CERCLA (Comprehensive Environmental Response, Compensation, and Liability) Act (1980), 4:306
Cereal foods, 3:81
Cerium, 1:208
Cervix, 3:153
Cesarean section, 3:156–157
Cesium, 1:170
Cetaceans, 3:221–222
CFCs. *See* Chlorofluorocarbons
Chadwick, James, 1:71, 1:80, 1:93
Challenger space shuttle explosion (1986), 1:257, 1:259, 1:294
Chang Heng (Chinese scientist), 4:234
Chaos theory, 4:24–25
Chaparral, 3:375
Charles, J. A. C., 1:52, 2:184, 2:241
Charles's law
airbags, 1:58–59, 56
buoyancy of balloons, 2:126
hot-air balloons, 1:55–56
molecular dynamics, 2:197
pressure, 1:52
thermal expansion, 2:249
Chase, Martha, 3:111
Cheerleaders, 2:140, 2:*141*
Cheetahs, 3:*373*
Chelicerata (subphylum), 3:275
Chemical bonding, **1:263–272,** 1:270*t*–271*t*
carbon, 1:244–245
chlorine, 1:232
compounds vs., 1:112–113
enzymes, 3:25
hydrogen, 1:253, 1:*265*
lipids, 3:35
minerals, 4:131
peptide linkage, 3:13, 3:18
Chemical deposition, 4:287–288
Chemical energy, 1:11, 2:177, 3:4–5, 3:360–361, 3:361
See also Kinetic energy; Potential energy
Chemical equations, 1:283–284
cellular respiration, 3:56
equilibrium, 1:298–299
photosynthesis, 3:5, 3:68
Chemical equilibrium, 1:19, **1:297–303,** 1:*298,* 1:302*t*–303*t*
Chemical ionization, 1:105
Chemical kinetics, 1:286
Chemical oceanography, 4:362
Chemical reactions, 1:34, **1:281–288,** 1:287*t*–288*t,* 1:289–290
biogeochemistry, 4:314–315
catalysts, 1:304–309, 3:24–25
equations, 1:297
fertilizers, 3:351
human digestion, 3:45–46
nitrogen, 4:331–332
peptide linkage, 3:13, 3:18–19
physical changes vs., 1:297–298
spicy foods, 3:297
Chemical symbols
Berzelius, Jons, 1:68–69
language, 1:122–123, 1:132–133

Chemical thermodynamics, 1:286
Chemical weathering, 4:265, 4:274
Chemiluminescence, 2:370–371
Chemoreception, **3:295–305,** 3:304*t*
Chemotherapy, 3:239
Chernobyl nuclear disaster (1986), 1:98, 1:*103*
Chestnut blight, 3:394
Chicago (IL), 1:*13*
Chichén-Itzá (Mayan pyramid), 4:*146*
Chickens, 3:322, 3:324, 3:328
Childbirth, **3:151–157,** 3:156*t*
Children
  mental development, 3:334
  sense of taste, 3:301
  vaccinations, 3:258
Chilean earthquake (1960), 4:237
Chimney sweeps, 3:240, 3:*240*
Chimneys, 2:116–117
Ch'in Shih-huang-ti, 2:8
China
  earthquakes, 4:236–237
  measurement standardization, 2:8
  wheelbarrows, 2:162–163
Chiropterans, 3:220
Chlorine, 1:231–232
Chlorofluorocarbons (CFCs), 1:233–234
  aerosol cans, 1:55, 2:188
  ozone depletion, 1:307
Chlorophyll, 3:*4,* 3:5
Chloroplasts, 3:*4*
Cholecystokinin (CCK), 3:10
Cholera, 3:*247*
Cholesteric liquid crystals, 1:43, 2:213
Cholesterol, 3:*36,* 3:36–37
Chordata (phylum), 3:205
Chorionic villi, 3:155–156
Chromium, 1:192, 3:78
Chromosomes, 3:99–100, 3:*102,* 3:111–112, 3:117, 3:126, 3:135
Chronobiological study, 3:315
Chronostratigraphy, 4:95, 4:106–108
Chrysler PT Cruiser, 2:109
Cigarette lighters, 1:*206*
Cinder cones, 4:258
Circadian rhythms, 3:306, 3:307–312, 4:83–84
Circannual cycles, 3:313
Circular motion. *See* Rotational motion
Circulatory system, 2:324, 3:230, 3:232
  See also Blood
Cirque glaciers, 4:378
Cirrocumulus clouds, 4:391
Cirrostratus clouds, 4:391
Cirrus clouds, 4:391
Cities. *See specific cities*
Cities as anthropogenic biomes, 3:378–379
Citric acid, 1:*312,* 1:315
Citrus fruits, 3:93
Cladistics, 3:192
Class I-III levers. *See* Levers
Classical physics
  five major divisions, 2:20
  frame of reference, 2:9–10
  friction, 2:56
  machines, 2:157–158
  relationship to modern physics, 2:20
  thermal expansion, 2:245–246
  See also Aristotelian physics; Newtonian physics
Classification. *See* Taxonomy
Claude, Georges, 1:241
Clausius, Rudolph Julius Emanuel, 2:222–223
Clay, 2:40–41, 4:*287*
Cleavage of minerals, 4:136
Cleft palate, 3:128
Clepsydras, 2:100–101, 2:163
Climate, **4:405–412,** 4:411*t*
  changes, 3:353
  classifying biomes, 3:372
  desertification, 4:309–310
  evapotranspiration, 4:390
  greenhouse effect, 4:355–356
  ice-core samples, 4:379
  mountains, 4:260
  See also Weather
Climatology, 4:407
Climax biological communities, 3:370–371, **3:400–409,** 3:407*t*–408*t*
Climax (ecology), 4:352
Cloning, 3:*121,* 3:122–123
  See also Genetic engineering
Clonorchis, 3:277
Closed systems (physics). *See* Systems
Clostridium botulinum, 3:252
Clothoid loops, 2:49–50
Cloud forests, 4:*345*
Cloud seeding, 4:404
Clouds
  altocumulus clouds, 4:*391*
  evapotranspiration, 4:390
  precipitation, 4:391–392
  seeding, 4:404
  types, 4:390–392
Clutches, 2:55
  See also Cars
Coaches, horsedrawn, 2:163
Coal, 4:*324,* 4:326
  See also Fossil fuels
Coal gasification, 1:*35,* 1:43, 1:46
Cobalt, 1:190–191
Cochlea, 2:317–318
Cockcroft, John, 1:*164,* 1:165
Coefficient of linear expansion, 2:246–248
Coefficient of volume expansion, 2:248

Coefficients, 2:7
coefficients of friction, 2:52–54
coefficients of thermal expansion, 2:246–248
G (gravitational coefficient), 2:73
lift, 2:105–106
pi, 2:7, 2:45
See also Numbers
Coenzymes, 3:25–26
Cohen, Stanley, 3:119
Coinage metals, 1:187–188, 1:294–295
Cold. *See* Heat
Cold, common
caused by virus, 3:60, 3:286–287
sense of taste and smell, 3:301–302
Cold climate
tundra, 3:374, 3:*394,* 3:394–395
See also Antarctica; Climate
Cold extrusion of metals, 2:151
Cold-blooded animals, 3:218
Collisions
cars, 2:41–43, 2:62–63
kinetic and potential energy, 2:175–176
linear momentum, 2:40–44
models, 1:298, 1:304
See also Elastic collisions; Inelastic collisions
Colloids, 1:42, 1:69, 1:332–333, 2:210–211
Colonization (movement of species), 3:*402,* 3:402–403
Colorado River delta, 4:*56*
Colors
interference, 2:290, 2:292
light, 2:358–360
perception, 2:359–360
spectrum, 2:355
See also Light; Primary colors
Columbus, Christopher
Earth's circumference, 4:45
magnetic declination, 4:46, 4:180
Combination reactions, 1:*283,* 1:285
Combustion, 1:291–292
Combustion engines, 1:*51,* 1:292
Commensalism (symbiosis), 3:273, 3:383–384, 3:389
Common chemical sense, 3:298, 3:*298*
Communications satellites, 4:*55*
Communities (animals), 3:323–324, 3:331
Compasses, magnetic, 2:334–335, 4:180
Competition in biological communities, 3:393–395
Complete migration, 3:336
Composite cones (volcanoes), 4:258
Compound levers, 2:162
Compound pulleys, 2:164
Compounds, **1:273–280,** 1:279*t*–280*t*
carbon cycle, 4:324–325
chemical bonding vs., 1:112–113
definition, 1:329–330
formation, 1:111
minerals, 4:131
mixtures vs., 1:*274,* 1:330–331, 1:338–339
molecular structure, 4:*315*
nitrogen, 4:334–336
noble gases, 1:237
Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) (1980), 4:306
Compressibility
aerodynamics, 2:102–103
airplanes, 2:106–107
gases, 2:183–184
See also Sonic booms
Compression
elasticity, 2:148
fluids and solids, 2:95–96
modulus, 2:148–149
stone, 4:*15*
Compton, Arthur Holly, 2:343
Compton Gamma Ray Observatory Satellite, 2:353
Concentration, 1:341, 1:*349*
Concentration camps, 3:*121*
Concrete, 2:151, 2:152
Condensation, 2:209–210, 4:372
Conditioning (behavior), 3:320–321
Conduction (heat), 2:220, 2:228, 4:186
Conductivity, electrical, 2:228
Congenital disorders, 3:128–131, 3:*129,* 3:155–156, 3:232
Coniferous forests, 3:371–372, 3:374
Conservation of angular momentum, 2:30
constant orientation, 2:33
skating, 2:27, 2:*29,* 2:33
tops, 2:33
tornadoes, 4:399
See also Angular momentum
Conservation of electric charge, 2:30–31
Conservation of energy, 2:28–29, 4:194–195
Bernoulli's principle, 2:112
Earth and energy, 4:198–199
gasoline and motors, 2:27
hydroelectric dams, 2:176
kinetic and potential energy, 2:174–176
matter, 2:203–205
mechanical energy, 2:28–29
rest energy, 2:29, 2:179–180
thermodynamics, 2:218, 2:222, 2:223
See also First law of thermodynamics
Conservation laws, **2:27–33,** 2:32*t*
See also specific laws
Conservation of linear momentum, 2:30
rifles, 2:*28,* 2:31, 2:38
rockets, 2:31, 2:33, 2:39
See also Linear momentum
Conservation of mass, 2:30, 2:203–205
Conservation of matter, 2:179–180, 2:203–205

Constant composition, 1:68, 1:329–330
Contagious diseases. *See* Infectious diseases
Containers and fluid pressure, 2:142
Continental crust, 4:229
Continental drift
  evolution and, 3:169, 3:180
  impact of massive asteroid, 3:185
  plate tectonics, 4:220–222
  seismology, 4:231–232
Continental shelves, 3:377
  See also Plate tectonics
Controversies
  cloning, 3:123
  DNA evidence, 3:108
  evolution, 3:165–169
  genetic engineering, 3:103–104, 3:121–122
  in vitro fertilization, 3:144
  logging, 3:408–409
Convection, **4:185–191,** 4:189*t*–190*t*
  cooking, 2:348
  heat, 2:228–229
  thermodynamics, 2:220–221
  thunderstorms, 4:398
  wind, 4:397
Convective cells, 4:186–188
Convergence (plate tectonics), 4:224
Conversion of mass to energy, 1:33
Coon Creek (WI) erosion, 4:286
Coordinates, 2:6
  See also Axes; Cartesian system; Graphs; Points
Copernicus, Nicholas, 4:*37*
  frame of reference, 2:9–10
  gravity, 2:70–71
  heliocentric system, 4:9, 4:38, 4:*40,* 4:65
  laws of motion, 2:61
  See also Heliocentric universe
Copper, 1:188, 1:289–290, 3:78, 4:138–139
Coral reefs, 3:377, 3:*377,* 4:*327*
Core (Earth), 4:182, 4:209–210, 4:214–215
Corn, 3:82, 3:387
Corpuscular theory of light, 2:290, 2:296, 2:342–343, 2:355–356
  See also Light; Photons
Correlation in stratigraphy, 4:108–109, 4:112
Corrosion, 1:294
Corundum, 4:137, 4:162, 4:164–165
Cosine. *See* Trigonometry
Cosmic background radiation, 1:*240*
Cosmology, 4:63–65, 4:68, 4:71
Cotton, 1:*373*
Coulomb, Charles, 2:340, 4:177–178
Count Rumford. *See* Thompson, Benjamin
Couper, Archibald Scott, 1:267
Courtship. *See* Mating rituals
Cousins, 3:115–116
Cousteau, Jacques, 2:124
Covalent bonding, 1:113, 1:268, 1:269, 1:364
Cowbird, 3:274
Cowpox, 3:256–257, 3:*257*
Cows. *See* Cattle
Cranes (machines), 2:164
Crash tests, 2:*63*
Crater Lake (OR), 4:*259*
Cream, 2:49
Creation science, 3:163, 3:168, 4:11
Creation story (Bible), 4:5, 4:6–7, 4:11
Creationism, 3:163, 3:168, 4:11
Creep (geology), 4:266, 4:275–276
Creutzfeldt, Hans Gerhard, 3:232–233
Creutzfeldt-Jakob disease, 3:128, 3:232–233
Crick, Francis, 2:298, 3:111, 3:117
Criminal investigations. *See* Forensics
Critical damping, 2:266
Critical point, 2:198
Crookes, William
  electromagnetism, 1:69–70
  electrons, experiments with, 1:86
  thallium, discovery of, 1:158
Crops, 3:136, 3:209, 3:350–351, 3:352, 3:380
  See also Agriculture; Plants
Crosscurrent exchange, 3:58
Cruise missiles, 2:82–83
Crumple zones in cars, 2:41–43
Crust (Earth). *See* Lithosphere
Crystalline solids, 1:104, 1:111
Crystals
  calcite with quartz, 4:*136*
  carbon, 4:325–326
  crystalline matter, 2:210
  elasticity, 2:151–152
  igneous rocks, 4:148–149
  jewels, 4:165
  lasers, 2:369
  melting, 2:207–208
  minerals, 4:132–133, 4:144
  piezoelectric devices, 2:322–323
  snowflakes, 4:*392*
  thermal expansion, 2:249–250
  x-ray diffraction, 2:298
  x-rays, 2:353
Ctesibius of Alexandria, 2:101, 2:163
Cumulonimbus clouds, 4:*187,* 4:187–188, 4:391–392
  See also Thunderstorms
Cumulus clouds, 4:391
Curie, Marie, 1:*224,* 2:*366,* 2:367–368
  polonium, discovery of, 1:226–227
  radioactivity, 1:70
  radium, discovery of, 1:178–179
Curie, Pierre, 1:70
Curium, 1:202
Currents
  hydrology, 4:363–364

whirlpools, 4:*363*
Curve balls
Bernoulli's principle, 2:117–119
projectile motion, 2:80–82
Curves in roads. *See* Roads
Cuvier, Georges, 4:92
Cycles (harmonic motion)
acoustics, 2:311
resonance, 2:279
See also Harmonic motion; Oscillations; Waves
Cycloalkanes, 1:368
Cyclones, 4:400–402, 4:*401*
See also Natural disasters
Cyclotrons, 1:201
Cypridina, 2:370
Cystic fibrosis, 3:62, 3:128

D

Dahn, Jeff, 1:164–165
Dalton, John, 1:*64*
atomic mass, 1:78–79
atomic theory, 1:68, 1:128, 1:264–265, 2:205
atoms, discovery of, 1:112, 2:195
Dalton's law of partial pressure, 1:54
Damping (energy), 2:266
Dante's Peak (movie), 4:17
Dark matter, 1:42, 2:211
Darwin, Charles, 3:*162*
Darwin's moth, 3:138
ethology, 3:320
evolution, 4:4
introduces theory of evolution, 3:161, 3:169
taxonomy, 3:197–198
Darwin, Erasmus, 3:167
Dating techniques. *See* Absolute dating; Relative dating
Davis, William Morris, 4:245
Davisson, Clinton Joseph, 2:297
Davy, Humphry, 1:166, 2:361
DDT (dichlorodiphenyltrichloroethane), 3:*72,* 3:73, 4:358
Debye, Peter Joseph William, 2:297
Decibels, 2:314
Deciduous trees, 3:362, 3:373
Decomposers, 3:68, 3:69, 3:349, 3:361
biogeochemistry, 4:316–317
carbon cycle, 4:330
food webs, 4:200, 4:342
soil formation, 4:294, 4:296
Decomposition, 3:68, 3:69
See also Decomposers
Decomposition reactions, 1:285
Decompression, 1:*50*
Decompression chambers, 2:124
Decompression sickness, 2:123–124, 4:334
Deflagration of airbags, 1:59
Deforestation, 4:*353*
ecology, 3:365–366, 4:352–356
remote sensing, 4:57, 4:59
Deformation
elasticity, 2:150
stress, 2:148–149
Dehydration
fruits, 1:351
humans, 1:350
Deinonychus, 3:184
Delayed sleep phase syndrome, 3:311
Delesse, Achilles, 4:225
Delta wing kites, 2:108
Deltas, river, 3:351, 4:*56,* 4:268, 4:300
Democritus, 1:67–68, 1:263, 2:205, 4:7–8
Dendochronology, 4:119
Denitrification, 4:338
Density, **1:23–30,** 1:29*t,* **2:21–26,** 2:25*t*
aerodynamics, 2:102–103
buoyancy, 2:121
Earth, 2:*23*
gold, 1:*25*
minerals, 4:136–137
planets, 4:66–67, 4:210
Saturn, 1:*26*
See also Viscosity
Dental health and fluoride, 1:233
Denver (CO), 2:146
Deoxyribonucleic acid. *See* DNA (deoxyribonucleic acid)
Department of Energy (U.S.), 3:103, 3:120
Deposition of sediments, 4:287–288, 4:290–291
Depositional environments, 4:288
Depth, 2:144–145
Dermoptera, 3:220
Descartes, René, 2:6, 3:306–307
Desert tortoises, 3:*351*
Desertification, 3:353, 4:306–310
Deserts
biomes, 3:375
formation of, 3:353
soil, 3:350, 3:*351,* 4:297–300
Designer proteins, 3:21–22
Desmodus rotundus, 3:220
Destructive interference, 2:290
Detritivores
biogeochemistry, 4:316–317
energy, 3:69, 3:361
food webs, 3:68, 3:349, 4:200, 4:342
soil formation, 4:294, 4:296
speciation, 3:221
Deuterium, 1:95–97, 1:254–255
atomic mass, 1:80, 1:131
hydrogen bombs, 1:*93,* 1:255

Developing nations
deforestation, 4:353–354
starvation, 3:84–85
Devils Tower (WY), 4:5, 4:270–271
Devonian period, 3:182, 3:183
Dewar, James, 2:200
Dextrose, 3:3–4
Diabetes mellitus, 3:242–243
Diamagnetism, 2:332
See also Magnetism
Diamond, Jared, 2:107, 3:395, 4:343
Diamonds, 1:246, 4:137–138, 4:165, 4:325–326
Diana (Princess of Wales), 3:*38*
Diaphragm (anatomy), 2:315, 2:320–321
Diastolic pressure, 2:147
Diet. *See* American Diet; Fitness; German Diet; Nutrition and nutrients
Differential migration, 3:336
Diffraction, **2:294–300,** 2:299*t,* 2:356
Diffraction gratings, 2:297, 2:298
Diffractometers, 2:298
Diffusion and respiration, 3:56–57, 3:*57*
Digestion, human, **3:44–54,** 3:52*t*–53*t*
breakdown of amino acids, 3:14–15
digestive system, 3:45–47, 3:*46,* 3:276, 3:278, 3:285–286
enzymes, 3:27
importance of cellulose, 3:8
metabolism, 3:33–34
Digital photography in geoscience, 4:55–56
Dilution, 1:341
Dinitrogen. *See* Nitrogen
Dinoflagellates, 2:369–370
Dinosaur National Monument (CO), 4:*117*
Dinosaurs, 3:*183,* 3:183–185
endothermy, 4:127–128
fossil excavations, 4:*117*
tyrannosaurus rex fossil, 4:*115*
Dinuguan (Filipino delicacy), 3:302–303
Diploid cells, 3:99
Dipole-dipole attraction, 1:113
Dipoles, 1:47
Dirigibles, 2:105, 2:127–128
See also Airships
Disaccharides, 3:4
Discordance (acoustics), 2:290
Discourses and Mathematical Demonstrations Concerning Two New Sciences (Galileo), 2:16–18
Diseases, human, **3:229–235,** 3:234*t*
beriberi, 3:92, 3:93–95
cancer, 3:21
congenital disorders, 3:128–131, 3:*129,* 3:155–156, 3:232
digestive disorders, 3:48–50
eating disorders, 3:38–40
ecosystems, 4:344–345
ethnic groups, 3:113, 3:127, 3:131
genetic disorders, 3:*113,* 3:113–116, 3:121, 3:127
Hartnup disease, 3:15
infectious diseases, **3:244–252,** 3:396
kwashiorkor, 3:85
neurological disorders, 3:302
noninfectious diseases, **3:236–243**
parasites, 3:275–282
pellagra, 3:15, 3:95
respiratory disorders, 3:60, 3:62
rickets, 3:*90,* 3:91
risk factors, 3:239–241
scurvy, 3:93
sickle-cell anemia, 3:*14,* 3:15–16
sleep disorders, 3:309–311
social impact, 3:246, 3:247–248
unknown causes, 3:*233*
Vitamin A poisoning, 3:89–90
Disk drives, 2:337
Displacement
ships, 2:122
volume measurement, 2:23–24
Dissociation, 1:321–322
Dissolved load, 4:285
Distillation, 1:40, **1:354–360,** 1:*357,* 1:359*t,* 2:209–210
Distilled water, 1:356
Distortion (acoustics), 2:326
Divergence (plate tectonics), 4:224, 4:*225*
Divine Comedy (poem), 4:215
Diving, underwater. *See* Underwater diving
Diving bells, 2:123
Dixon, Jeremiah, 4:47
DNA (deoxyribonucleic acid)
asexual reproduction, 3:135
cancer, 3:238
effect of viruses on, 3:285, 3:287
forensics and criminal investigations, 3:*20,* 3:21, 3:103, 3:104–105, 3:*105,* 3:108
genes, 3:100–101, 3:117–118, 3:*118,* 3:119, 3:126, 3:164–165
history, 3:111
molecules, 1:*111*
nanocomputer, 3:120
phylogeny, 3:198
synthesis of amino acids, 3:13
Doctors, medical, 3:153–154, 3:238–239
Dodecahedrons, 4:*133*
Dodo (bird), 3:208–209, 3:*209*
Dog whistles, 2:323
Dogs
human interaction with, 3:383, 3:387
Pavlov's dog, 3:320
sense of smell, 3:298, 3:303
ultrasonics, 2:323
Dolly (cloned sheep), 3:*122,* 3:123
Dolphins, 3:195, 3:204–205, 3:221–222, 3:340–341

Domain alignment, 2:332–334
Domain growth, 2:332–334
Domesticated animals, 3:387, 3:395–396
Dominant genes, 3:112–113
Donald, Ian, 2:324
Donkeys, 3:215
Doorbells, 2:336
Doors, 2:89
Doping agents, 1:226
Doppler, Christian Johann, 2:303–304
Doppler effect, **2:301–307,** 2:306*t,* 2:324
Doppler radar, 2:*303,* 2:305, 4:403–404
Dorn, Friedrich, 1:239
Double-displacement reaction, 1:285
Double-helix model (DNA), 3:111, 3:117–118, 3:*118*
  See also DNA (deoxyribonucleic acid)
Down syndrome, 3:126, 3:129, 3:*129*
Downs cells, 1:166
Drafting (aerodynamics), 2:109
Drafts (air currents), 2:98
Drag (aeronautics)
  airplanes, 2:106
  birds, 2:104–105
  cars and trucks, 2:109–110
  See also Induced drag
Dreissena polymorpha, 3:211
Drinking water and fluoridation, 1:233
Drizzle, 4:392
Drought and mud cracks, 4:*287*
Drugs and medicines
  ecstasy, 3:315
  impact on taste and smell, 3:302
  insulin, 3:120, 3:242–243
  LSD (lysergic acid diethylamide), 3:307
  used in childbirth, 3:154
Dry ice, 1:248, 4:*402,* 4:404
Dry valleys (Antarctica), 4:379
Dryja, Thaddeus R., 3:13
Du Fay, Charles, 2:340
du Pont de Nemours and Company, E. I.
  nylon, 1:378
  organic chemistry, 1:365–366
Ducks, 3:193, 3:330
Duodenum, 3:47, 3:48
Dürer, Albrecht, 4:15–16
Dust bowls, 3:352
  dust storms, 4:*303*
  erosion, 4:270
  sediment, 4:286
  soil conservation, 4:304–305
Dust devils, 4:*269*
Dust mites, 3:*265*
Dutch elm disease, 3:210
Dwarfism, 3:129
Dye lasers, 2:361–362
Dynamics, **2:13–20,** 2:19*t*
  See also Aerodynamics; Fluid dynamics; Hydrodynamics; Molecular dynamics; Thermodynamics
Dysprosium, 1:210

E

E. I. du Pont de Nemours and Company. *See* du Pont de Nemours and Company, E. I.
E. coli bacteria, 3:*51,* 3:285–286
Eardrums, 2:317
Ears
  bats, 3:340
  hearing, 2:316–318
  human ear infections, 3:290
  whales, 3:341
Earth
  age, 4:89–90, 4:94, 4:98–99
  alkali metals, 1:164
  alkaline earth metals, 1:174
  asthenosphere, 4:212–214
  biological communities, **3:391–399, 3:400–409**
  biomes, **3:370–380**
  biosphere, **3:345–359**
  circumference, historical estimates, 4:38
  climate changes, 4:410–411
  core, 4:182, 4:209–210, 4:214–215
  density, 1:*26,* 2:*23,* 4:66–67
  Earth-Moon system, 4:*73,* 4:74–75
  element abundance, 4:130, 4:313–314
  energy, **4:192–206**
  energy output, 4:198–199
  energy sources, 4:195–198
  geologic time periods, 3:179
  geomagnetic field, 2:334–335, 3:338–339
  geomagnetism, 4:180–182, 4:184
  glossaries, 4:81*t*–83*t,* 4:216*t*–217*t*
  gravity, 2:75–77, 4:65–66, 4:173–174, 4:176
  greenhouse effect, 3:366, 3:368–369
  historical map, 4:*16*
  interior, **4:209–218,** 4:237, 4:240–241
  islands, 4:249
  lithosphere, 4:212–213
  Mercator map, 4:*46*
  mesosphere, 4:214
  metals, 1:151–152
  natural systems, **4:23–31**
  noble gases, 1:239–240
  nonmetals, 1:216, 1:224
  origin of life, 3:17, 3:177–178, 3:180–181, 3:217
  origins, 4:87–88
  planetary science, 4:65–67
  plate tectonics, 4:209–211
  plates, 4:223–224
  relative motion, 2:9–10

relief map, 4:*48*
rotation, 2:268–269, 3:308
roundness, 2:76–77
soil formation, 4:292–293
solar system, 4:72–84
spheres, 4:25–27
struck by massive asteroid, 3:185–186, 3:*186*
transition metals, 1:186
water, 4:369–371, 4:387–388
weather, 4:397
Earth sciences
Earth systems, **4:23–31**
Earth's spheres, 4:25–27
geography, **4:44–52**
scientific method, **4:3–11**
See also Geoscience; Hydrology; Weather
Earthquakes
damage, 4:*236*
plate tectonics, 4:228
predictions, 1:240
seismology, 4:233–237
See also Natural disasters; Seismology
Earthworms, 3:349
East Pacific Rise, 4:*221*
Eating disorders, 3:*38,* 3:38–40
Eating habits, human, 3:39, 3:48, 3:49, 3:242, 3:311
Eavesdropping devices, 2:325
Ebola virus, 3:250–251
Echolocation, 3:*339,* 3:339–341
Ecology, **3:360–369,** 3:367*t*–368*t,* 3:391, **4:351–358,** 4:356*t*–357*t*
Economic geology, **4:154–165,** 4:163*t*–164*t*
See also Geology
Ecosystems, **4:341–350**
biological communities, **3:391–399**
biomes, **3:370–380**
climate zones, 4:407
ecology, **3:360–369,** 4:351–352
glossaries, 3:367*t*–368*t,* 4:348*t*–349*t*
islands, 4:251–252
microclimates, 4:407–409
mountains, 4:256, 4:260, 4:262
soil, 4:297–300
tropical cloud forests, 4:*345*
See also Food webs
Ecstasy (drug), 3:315
Ectothermy in dinosaurs, 4:127–128
Edison, Thomas, 2:360, 2:361, 2:369, 3:*312*
Edwards, Robert G., 3:144
Efficiency, machine. *See* Machine efficiency
Efficient causes (philosophy), 4:3–5
Egg cells, 3:100, 3:136
Eggs
bird parasites, 3:274, 3:330–331
egg-laying mammals, 3:218
human, 3:143
Egypt
fertile soil, 3:350–351
pyramids, 2:162, 2:164–165
Ehrlich, Paul, 3:255
Eijkman, Christiaan, 3:93–95
Eilmer, 2:105
Einstein, Albert, 1:72–73
Bose-Einstein Condensate, 2:201–202, 2:211
electromagnetism, 2:343
gravity, 2:77
light, 2:297
molecular dynamics, 2:196, 2:206
optics, 2:357
relativity, 2:10–12, 2:29, 2:303
El Niño consequences, 4:28, 4:30
Elastic collisions, 2:*38,* 2:40–44
Elastic deformation, 2:150
Elastic limit, 2:148
Elastic potential energy, 2:264–266
Elasticity, **2:148–154,** 2:153*t*–154*t*
See also Elastic deformation
Elastomers
elasticity, 2:152
oscillations, 2:267
Elderly
Alzheimer's disease, 3:234
sense of taste, 3:301
Electric charges
atoms, 1:65–66
ions, 1:101–108
Electric current
electromagnetism, 2:341–342
measurement, 2:21
Electric discharge, 4:*182*
Electric engines, 2:90
Electric thermometers, 1:17, 2:242–244
Electric vehicles, 1:*163*
Electrical conductivity, 2:228
Electrical generators, 2:341
Electricity and Magnetism (Maxwell), 2:356–357
Electrochemistry, 1:296
Electromagnetic induction, 2:341
Electromagnetic radiation, 2:341–344
electron behavior, 1:87
ionization, 1:105–106
photosynthesis, 3:4–5
Electromagnetic spectrum, **2:340–353**
light, 2:357–358
luminescence, 2:365–366
solar radiation, 4:197
See also Electromagnetism
Electromagnetic waves, 2:341–342
frequency, 2:276–277
interference, 2:290, 2:292–293
light, 2:356–357

properties, 2:256
resonance, 2:282–283
Electromagnetism, **2:340–353,** 2:351*t*–352*t*
atomic theory, 1:69–70
classical physics, 2:20
discovery, 2:20
electric discharge, 4:*182*
electromagnetic energy, 4:193
electromagnetic radiation, 2:221, 2:229
gases, 1:48–49
geomagnetism, 4:177–180
light, 2:356–358
luminescence, 2:365–367
machines, 2:157
magnetism, 2:331–334
molecular dynamics, 2:194–195
molecules, 2:207
Electromagnets
iron, 2:334
sound devices, 2:336
See also Magnets
Electron-dot diagrams, 1:*264*
Electron impact ionization, 1:105
Electron tubes, 2:345
Electron volts (unit of measure), 2:345
Electronegativity, 1:113, 3:297
carbon, 1:244, 1:364
minerals, 4:131
Pauling, Linus, 1:269
Electronic amplification, 2:315
Electronic distance measurement, 4:49
Electrons, **1:84–91,** 1:*85,* 1:90*t*–91t
atomic structure, 1:35, 1:66–67, 1:92, 1:130, 1:135
behavior, 1:63–65
chemical bonding, 1:267–268
diffraction, 2:297
discovery, 2:206
identified, 1:79
magnetism, 2:331
orbitals, 1:142
Electrostatics, 2:340
Element symbols. *See* Chemical symbols
Elements, **1:119–126,** 1:120*t,* 1:124*t*–125*t*
abundance, 4:313–314, 4:332–333
Aristotle, 1:67–68
atomic numbers, 1:65
atoms, 1:63–64
biogeochemistry, 4:313–314
Boyle, Robert, 1:68
carbon cycle, 4:324–325
in the human body, 3:78
minerals, 4:130
models, 1:*110*
native elements, 4:133–134
nitrogen, 4:332–333
periodic table, 1:69, 1:132
solar system formation, 4:72–74
See also Families of elements
Elements, Aristotelian. *See* Aristotelian physics
Elephantiasis, 3:*278,* 3:279
Elephants, 3:200, 3:222
Elevation. *See* Altitude
Embryo, 3:152–153
$E=mc^2$. *See* Relativity; Rest energy
Emission (luminescence), 2:366–367
Empedocles, 4:8
Emulsifiers, 1:333–334, 1:342–343
Endangered species, 3:207–208, 3:223
See also Extinction
Endogenous infection, 3:283
Endothermy in dinosaurs, 4:127–128
Energy, **2:170–180,** 4:203*t*–205*t*
alternative energy, 4:202, 4:206
earth, **4:192–206**
Earth systems, **4:23–31**
electromagnetic spectrum, 2:345
food webs, 4:342
human body, 3:10, 3:36, 3:308
hydrologic cycle, 4:388–389
interference, 2:288–289
matter, 1:33
metabolism, 3:33–34, 3:44, 3:80
moves from environment to system, 3:345, 3:360–361
produced in chemical reactions, 3:24
Sun, 4:78
Sun's energy used by plants, 3:67–69
temperature and heat, 1:11, 4:193–195
thermodynamics, 2:217–218
transfer, 2:*171,* 3:69, 3:393
work, 4:192–193
See also Kinetic energy; Mechanical energy; Potential energy; Rest energy
Energy conservation. *See* Conservation of energy
Engine coolant, 2:248
Engines
combustion, 1:*51*
gas laws, 2:188–189
torque, 2:90–91
See also Cars; Electric engines
English measurement system, 1:7–8, 2:8–9
See also Measurements; Metric system
The Englishman Who Went Up a Hill But Came Down a Mountain (movie), 4:255
Entamoeba histolytica, 3:276
Enterobiasis, 3:278
Entropy, 1:13–14, 2:222–223
Earth and energy, 4:198

second law of thermodynamics, 2:222–223, 2:232, 2:234, 4:195
third law of thermodynamics, 2:223, 2:234–235
See also Second law of thermodynamics
Environment, 3:345–346
Environmental concerns
biomagnification, 4:356–358
desertification, 3:353, 4:306–310
forest conservation, 3:363, 3:408–409
fossil fuels, 4:201–202
mining, 4:162
Ogallala Aquifer (U.S.), 4:373
oil industry, 4:158–159
plastics, 1:376–377
recycling, 1:380
soil conservation, 3:352
tropical rain forests, 3:350
See also Dust bowls; Global warming; Pollution
Environmental geology, 4:18
Enzymes, 1:306–307, 3:21, **3:24–30,** 3:29*t*–30*t,* 3:37, 3:119
Eohippus (horse ancestor), 3:172
Eolian processes. *See* Wind erosion
Eötvös effect, 4:172
Eötvös, Roland, 4:172
Epidemiology, 3:237
Epinephrine, 3:267–268
Epiphytic plants, 3:389
Epirogenesis. *See* Tectonism
Epsom salts, 1:175
Equilibrium, **2:133–138,** 2:138*t,* 2:263–264
See also Dynamics; Statics
Eratosthenes of Cyrene, 4:38, 4:45
Erbium, 1:209
Ericsson, John, 2:166
Erosion, **4:264–272,** 4:271*t*
beaches, 4:*284*
dust bowls, 3:352
Nicola River Canyon (British Columbia), 4:*265*
prevention, 4:305
rock arches, 4:*267*
sandstone, 4:*26*
sedimentation, 4:284–285
Escherichia coli bacteria, 3:*51,* 3:285–286
Eskimo curlews, 3:208
Esophagus, 3:45
Esters, 1:369
Estuaries, 3:377
Ethanol, 1:*340,* 1:343, 1:356–357
Ether (optics), 2:356
Ethics of genetic engineering, 3:103–104, 3:122
Ethology, 3:320
Ethylene dibromide, 1:234
Eugenics, 3:121–122
Euler, Leonard von, 2:113
Europe
diseases, 4:344–345
early humans, 3:162
Europium, 1:210
Eustachian tubes, 2:317
Eutrophication, 3:354, 4:318
Evaporation, 2:208–209, 4:*370*
evaporite minerals, 4:290–291
evapotranspiration, 4:389
hydrologic cycle, 4:370, 4:371, 4:373
See also Evapotranspiration
Evaporites, 4:290–291
Evapotranspiration, 3:346, 3:347, 3:354–355, 3:*355,* **4:387–394**
climate, 4:390
clouds, 4:390–392
evaporation, 4:389
glossary, 4:393*t*–394*t*
hydrologic cycle, 4:370, 4:371, 4:387–389
transpiration, 4:389–390
See also Evaporation
Evergreen forests. *See* Coniferous forests
Evolution, **3:161–175,** 3:174*t*–175*t*
amino acids dating, 3:17
choosing the ideal mate, 3:147–149
humans and food intake, 3:*82*
mammals, 3:221–222
moving from water to land, 3:181–182
primates, 3:220
role of mutation, 3:101, 3:127
trees, 3:364–365
See also Natural selection; Phylogeny
Ewing, William Maurice, 4:223
Exhalation (human breathing), 3:55–56
Exogenous infection, 3:283
Expansion joints, 2:250
Explorers and exploration
Barents, Willem, 3:88–89
Columbus, Christopher, 4:45, 4:46, 4:180
introduced species, 3:210, 3:395–396
Explosives, 1:292–294
ammonium nitrate, 3:351–352, 4:*333*
explosions, 1:292–294
impact of massive asteroid, 3:185
Exposure to lead, 1:158
Extinction
dodo bird and dodo tree, 3:208–209, 3:*209*
mass extinctions, 3:181, 3:182–183, 3:185–186
See also Mass extinctions
Extreme Ultraviolet Explorer, 2:350
Eyes
color vision, 2:359–360
diseases, 3:279
heredity, 3:112–113

F

F layer (ionosphere), 2:346
Facial characteristics, 3:*129,* 3:129–130
Facilitation model (biological communities), 3:401
Facultative relationships (symbiosis), 3:273–274, 3:383–384
Fahrenheit, Daniel, 2:240
Fahrenheit temperature scale, 1:14–15, 2:240–241
Fall (geology), 4:267–268, 4:277
Families of elements, **1:140–147,** 1:145*t*–146*t*
  alkaline earth metals, 1:171–172
  halogens, 1:229
  metalloids, 1:222
  metals, 1:153
  nonmetals, 1:213–215
  transition metals, 1:181
  See also Elements
Faraday, Michael, 1:85, 2:200, 2:341, 4:178
Farming
  nitrogen cycle, 4:338
  soil, 4:300
  soil conservation, 4:304–305
  See also Agriculture
Fast food, 3:79, 3:81
Fat, human body, 3:10, 3:35–37, 3:*36,* 3:88, 3:127, 3:*146,* 3:147, 3:307
Fats and oils, 3:35–37, 3:44–45, 3:81, 3:88, 3:297
  See also Lipids; Oils
Fault-block mountains, 4:257
Faults (geology), 4:224, 4:*231*
Faunal dating, 3:172, 4:119
Fax machines, 2:267–268
FCC (Federal Communications Commission), 2:276–277, 2:346–347
FDA (Food and Drug Administration), 3:79
Feces, human, 3:50–54
Federal Communications Commission (FCC), 2:276–277, 2:346–347
Feedback, 2:283, 4:27–28
Felidae, 3:221
Female reproductive system, 3:143, 3:152–153
Fens, 3:376
Ferdinand II (Grand Duke of Tuscany), 1:14, 2:239
Fermat, Pierre de, 2:6
Fermentation, 3:25, 3:*26,* 3:27–30, 3:*28*
Fermi, Enrico, 1:*94,* 1:97
Ferrimagnetism, 2:332–334
  See also Magnetism
Ferromagnetism, 2:332–334
  See also Magnetism
Fertilization (sexual reproduction), 3:136, 3:143–144, 3:*144*
Fertilizers, 3:351
Fetus
  development, 3:152–153, 3:*155,* 3:155–156
  similarities among animals, 3:170
Feynman, Richard, 1:34, 2:205
Fiber in human diet, 3:50
  See also Cellulose
Fiber-optic communications, 2:364
Field ionization, 1:*102,* 1:105
Field mice, 3:163–164
Fighting (behavior)
  defending territory, 3:*323*
  displays, 3:324–326
  mating rituals, 3:145–146
Filaments (light bulbs), 2:361
Fill dirt, 4:295
Filtration, **1:354–360,** 1:*356,* 1:359*t*
Final causes (philosophy), 4:3–5
Fingerprints, 3:*20,* 3:105
Fir trees, 4:*318*
Fire
  friction, 2:56
  light, 2:360
Fire extinguishers, 1:55, 2:*185,* 2:187
Fireworks, 1:*174*
Firnas, Abul Qasim Ibn, 2:105
First harmonic, 2:*273,* 2:274
First law of motion, 2:18–19
  centripetal force, 2:46–47
  friction, 2:59–61
  gravity, 2:72
  See also Inertia
First law of thermodynamics, 2:216, 2:222, 2:232, 4:194–195
  Earth and energy, 4:198–199
  food webs, 3:69
  See also Conservation of energy
Fischer, Emil, 3:25
Fish
  behavior, 3:322, 3:327–328
  bioaccumulation, 3:73, 3:76
  buoyancy, 2:122, 2:*123*
  evolutionary history, 3:195
  food webs, 3:*70,* 3:71
  introduced species, 3:210
  migraton, 3:*337*
  origin of life, 3:181–182, 3:183
  respiration, 3:57
  speciation, 3:217
  sushi, 3:*302,* 3:303
  See also Aquatic animals
Fish finders, 2:*321*
Fishing rods, 2:161–162
Fishing sonar, 2:*321*
Fission (asexual reproduction), 3:135, 3:285
Fitness
  exercise, 3:37
  ideals, 3:147
  weight loss programs, 3:37, 3:81
The Five Biggest Ideas in Science (book), 4:222

Fixed-action patterns, 3:322, 3:*322,* 3:327–328
Flaps (airplanes), 2:106
Flatulence, 3:54
Flavonoids, 3:141
Flavored oxygen, 1:*215*
Fleas, 3:282
Fleming, Alexander, 3:290
Flood, biblical, 4:6
Flooding, 4:364–366, 4:*365*
Flow (geology), 4:266, 4:*276,* 4:276–277
Flowering plants. *See* Angiosperms; Plants
Fluid dynamics
  aerodynamics, 2:102–103
  Bernoulli's investigations, 2:20
  fluid mechanics, 2:95
  See also Aerodynamics; Dynamics; Fluid mechanics; Fluids; Hydrodynamics
Fluid mechanics, **2:95–101,** 2:100*t*
  See also Fluid dynamics; Fluids
Fluid pressure, 2:140–147
  Bernoulli's principle, 2:143–144
  buoyancy, 2:121, 2:144–145
  characteristics, 2:142
  force and surface area, 2:140–141
  glossary, 2:146*t*
  human body, 2:145–147
  measurements, 2:141–142
  Pascal's principle, 2:142–143
  water pressure, 2:142
Fluids, 2:95–96
  See also Fluid dynamics; Fluid mechanics
Flukes, 3:277
Fluorescence, 2:368–370
Fluorescent bulbs, 2:*367,* 2:369
Fluoridation of water supplies, 1:233
Fluorine, 1:232–234, 1:269
Flywheels
  friction, 2:55
  torque, 2:89–90
  See also Cars; Gyroscopes
FM radio broadcasts, 2:345–346
Foliation (rocks), 4:152
Folk science and taxonomy, 3:195–196
Food chains. *See* Food webs
Food and Drug Administration (FDA), 3:79
Food preservation, 1:351–353
Food Security Act (1985), 4:305
Food webs, **3:67–76,** 3:74*t*–76*t,* 4:351
  competition, 3:393
  ecosystems, 3:360–361, 4:341–342
  energy, 4:200
  marine, 3:376–377
Foods
  bacteria, 3:285
  cultural attitudes, 3:*302,* 3:302–303
  improper cooking and handling, 3:245, 3:251, 3:277–278
  nutrition labels, 3:79
  produced by lactic acid, 3:59–60
  spoilage, 3:27
  taste, 3:297, 3:299–301
  USDA food pyramid, 3:81
  See also Crops; Meat
Force, 2:18–19, 2:46–47, 2:65–66
  centripetal force, 2:45–50
  gravitational force, 2:75–77, 2:171–173
  impulse, 2:39–44
  machines, 2:157–169
  paired forces, 2:66–67
  strong nuclear force, 2:157
  weak nuclear force, 2:157
  See also Acceleration; Energy; Mass; Second law of motion; Torque; Vector measurements; Work
Forced convection, 2:228–229, 4:186
Forceps, 3:153–154
Forensics
  criminal investigation, 3:*20,* 3:21, 3:103, 3:104–105, 3:*105,* 3:108
  forensic geology, 4:19–21
Forestry. *See* Logging and forestry
Forests
  biological communities, 3:371–374, 3:403
  carbon content, 3:369
  deforestation, 3:365–366, 4:352–356
  ecology, 3:361–363
  ecosystems, 4:346–347
  old-growth, 3:406, 3:408–409
  specialized climate, 3:*362*
  tropical cloud forests, 4:*345*
Formal causes (philosophy), 4:3–5
Fossil fuels
  bioenergy, 4:201
  carbon cycle, 4:326
  economic geology, 4:158–160
  environmental concerns, 4:201–202
  global warming, 4:409
Fossils
  correlation, 4:112
  excavation, 4:122–123
  fossil record, 3:*171,* 3:171–172, 3:217
  fossilization, 4:121–122
  geologic history, 4:121–122
  limestone, 4:*109*
  mineralization, 3:176
  stingray, 4:*121*
  tyrannosaurus rex, 4:*115*
  Vinci, Leonardo da 4:88, 4:105
Foucault, Jean Bernard Leon, 2:268–269, 2:281–282, 2:356
Foucault pendula, 2:268–269, 2:281–282

"Four causes," 4:3–5
Four elements (Greek physics), 2:15, 2:69–70, 4:7–8
Fractional distillation, 1:358
Frame of reference, **2:3–12,** 2:11*t*
  Doppler effect, 2:302–303
  geography, 4:51–52
Francisella tularensis, 3:252
Francium, 1:170
Franklin, Benjamin, 2:108, 2:340, 4:177
Franklin, Rosalind Elsie, 2:297–298
Fraunhofer, Joseph von, 2:297
Fraunhofer diffraction, 2:297
Freon, 1:*231*
Frequency, **2:271–277,** 2:275*t*–276*t*
  acoustics, 2:312–313
  Doppler effect, 2:301
  electromagnetic spectrum, 2:344
  electromagnetism, 2:343–344
  luminescence, 2:366
  modulation, 2:260–261
  oscillations, 2:263–264
  radio broadcasting, 2:345–347
  radio waves, 2:259–260
  resonance, 2:279
  sound waves, 2:259
  ultrasonics, 2:319–320, 2:321–322
  waves, 2:256–257
  See also Wavelength
Fresnel, Augustin Jean, 2:297
Fresnel diffraction, 2:297
Friction, **2:52–57,** 2:57*t*
  air resistance, 2:74–75
  conservation of angular momentum, 2:27
  conservation of linear momentum, 2:33
  first law of motion, 2:59–61
  kinetic and potential energy, 2:175–176
  luminescence, 2:371
  third law of motion, 2:66–67
  See also Air resistance
Frictionless surfaces, 2:54–55
Fried foods, 3:81
Frigate birds, 3:*145*
Frisbees, 2:33
Frisch, Karl von, 3:320, 3:323
Frisius, Gemma, 4:49
Frontal thunderstorms, 4:398–399
Fruits and vegetables
  artichokes, 3:6
  cabbage, 3:*26*
  healthy eating, 3:50, 3:81
  pineapples, 3:*137*
  preservation, 1:351–353
  source of carbohydrates, 3:5–9
  source of protein, 3:23
  source of vitamin C, 3:93
Fuel-injected automobiles, 1:56
Fulcrums, 2:160–162
Fullerenes, 1:246
Fundamental frequency, 2:*273,* 2:274
Fungi
  decomposers, 3:361
  kingdom, 3:198
  mycorrhizae, 3:384–386
Funnel clouds, 4:399–400
  See also Natural disasters
Fusion bombs. *See* Hydrogen bombs
Fusion (sexual reproduction), 3:135–136

G

G (gravitational coefficient), 2:73, 4:171
Gabor, Dennis, 2:299
Gadolinium, 1:208
Gagnan, Emile, 2:124
Gaia hypothesis, 4:27
Gal (unit of measurement), 4:172
Galactic movement, 2:307
Galactose, 3:115
Galápagos Islands, 3:169
Galaxies, 4:70–71
Galen (Greco-Roman physician), 2:239
Galilei, Galileo, 1:*12,* 4:*170*
  censure by Roman Catholic Church, 2:16, 2:18, 2:70–71
  frame of reference, 2:9–10
  gravity, 2:17–18, 2:70–71, 4:65, 4:170
  idealized models, 2:74
  kinematics and dynamics, 2:16–18
  laws of motion, 2:61–62
  pendula, 2:267, 2:274
  scientific method, 4:9–10, 4:38, 4:65
  telescopes, 2:354
  thermoscope, 1:14, 2:239
  Two New Sciences, 2:16–17
Galileo (space probe), 2:335
Gallium, 1:157
Galvanized steel, 1:188–189
Gametes, 3:100, 3:136
Gamma ray astronomy, 2:353
Gamma rays, 2:353, 2:366
Gas filtration, 1:358–359
Gas lasers, 2:361–362
Gas laws, 1:19, 1:51–52, **2:183–191,** 2:190*t*–191*t*
  fire extinguishers, 2:*185*
  hot-air balloons, 2:*186*
  molecular dynamics, 2:196–197, 2:210
  thermal expansion, 2:249
Gases, **1:48–59,** 1:57*t*–58*t*
  acoustics, 2:312, 2:321
  behavior, 2:183–184, 2:185–186
  boiling, 2:209

characteristics, 2:148
diffraction, 2:297
evaporation, 2:208–209
kinetic theory, 2:196–197
laws, 2:183–190
liquification, 1:39–40, 1:43
properties, 1:49*t*
resonance, 2:278
thermal expansion, 2:249
triple point, 2:6
volume, 1:27–28
volume measurement, 2:24
Gasohol, 3:30
Gasoline
conservation of energy, 2:27
thermal expansion, 2:248
Gastric juices, human, 3:45–46
Gateway Arch (St. Louis, MO), 2:79
Gauss, Carl Friedrich, 2:335, 2:340–341, 4:178
Gauss (unit of measure), 2:335
Gay-Lussac, Joseph, 1:78–79, 2:184
Gay-Lussac's law, 1:52–53, 1:56, 2:184, 2:312
Gazelles, 3:*373*
Gears, 2:163–164
Geese, 3:322, 3:328–329, 3:*329,* 3:330
Geike, Archibald, 4:91
Gellibrand, Henry, 4:88, 4:177
Gender determination, 3:111, 3:112
Gender differences
attitudes towards ideal mates, 3:145–149
body fat, 3:37
desirable characteristics, 3:*146*
eating disorders, 3:38
genetic disorders, 3:115
hemophilia, 3:241–242
reproductive system, 3:142–143
taste buds, 3:300–301
Generators, electrical, 2:341
Genes, **3:99–109, 3:117–125**
alleles, 3:112
cancer, 3:238
gene therapy, 3:103
Human Genome Project, 3:103–104
propensity to gain weight, 3:37, 3:127
single-cell life-forms, 3:206
speciation, 3:217
Genesis, Book of, 4:5–7, 4:11, 4:87–88
Genetic engineering, 3:102–103, **3:117–125,** 3:124*t*
Genetic recombination, 3:101
Genetics, **3:99–109,** 3:106*t*–108*t*
current research, 3:*102,* 3:118
in evolution, 3:164–165
history, 3:110–111
Genitals, human, 3:142–143, 3:238–239, 3:240
Genotype, 3:110, 3:112
Geoarchaeology, 4:18–19
Geocentric universe, 2:15, 4:64–65
Geochemistry, 4:43
See also Biogeochemistry; Geoscience
Geodesic domes, 1:*247*
Geodesy
geography, 4:49–50
gravity, 4:171–173
Geography, **4:44–52,** 4:50*t*–51*t*
See also Earth sciences; Surveying
Geoid, 4:171–172
Geologic maps, 4:44, 4:47–49
Geologic scale, 4:95
Geologic time, **4:95–103,** 4:102*t*–103*t,* 4:114–118
Geology
disciplines, 4:40, 4:42
geography, 4:44–45
history, 4:39–40
See also Economic geology; Geoscience
Geomagnetism, 4:50–51, **4:177–184,** 4:183*t*
geography, 4:50–51
magnetic fields, 2:334–335
Geomorphology, **4:245–252,** 4:250*t*–251*t*
erosion, 4:270–271
glaciology, 4:378, 4:380
mountains, 4:256
soil formation, 4:294–295
speciation, 4:262
See also Geoscience
Geomythology, 4:5–8, 4:87–88
Geophysics, 4:42–43
Geoscience, **4:12–21,** 4:20*t,* 4:41*t*–42*t*
disciplines, **4:35–43**
Earth systems, **4:23–31**
Earth's spheres, 4:25–27
history, 4:37–40
mythology, 4:5–8
remote sensing, **4:53–59**
scientific method, **4:3–11**
See also Earth sciences; Geochemistry; Geology; Geomorphology; Geophysics
Geosphere, 3:346, 4:26
See also Earth; Lithosphere
Geothermal energy, 4:197, 4:206
convection, 4:188
Earth's interior, 4:214
Germ (reproductive) cells, 3:99, 3:126–127
German diet, 3:81
German marks, 1:*4,* 1:6
Germanium, 1:226
Germs
bacteriology, 3:288, 3:290
disease-causing, 3:244, 3:283–284, 3:396
See also Bacteria; Viruses
Gessner, Konrad von, 3:197
Gestation, 3:152–153
Geysers, 4:*196*

Giardia lamblia, 3:276
Gilbert, William, 2:334, 4:180–181
Gills, 3:57
Glacier Bay (AK), 3:*404,* 3:405
Glaciers, 3:405
  characteristics, 4:377–378
  erosion, 4:268–269
  glaciology, **4:376–384**
  Kennicott Glacier (AK), 4:*381*
  sedimentation, 4:285
  See also Glaciology; Ice
Glaciology, **4:376–384,** 4:382*t*–383*t*
  See also Glaciers
Glands, human, 3:45
  diseases, 3:229–230, 3:242
  pineal gland, 3:306–307
  thymus gland, 3:263
Gliders
  Bernoulli's principle, 2:115–116
  flight, 2:105
Global positioning system, 4:52, 4:*54*
Global warming, 4:201–202, 4:355–356, 4:384, 4:409
  See also Greenhouse effect
Glomar Challenger (ship), 4:223
Glossaries
  acid-base reactions, 1:324*t*–325*t*
  acids and bases, 1:316*t*–317*t*
  acoustics, 2:316*t*–317*t*
  actinides, 1:202*t*–203*t*
  aerodynamics, 2:110*t*
  alkali metals, 1:169*t*
  alkaline earth metals, 1:178*t*–179*t*
  amino acids, 3:16*t*
  atomic mass, 1:82*t*–83*t*
  atoms, 1:74*t*–75*t*
  behavior, 3:325*t*
  Bernoulli's principle, 2:118*t*
  biogeochemistry, 4:319*t*–320*t*
  biological communities, 3:397*t*–398*t*
  biological rhythms, 3:314*t*
  biosphere, 3:356*t*–358*t*
  carbohydrates, 3:8*t*–9*t*
  carbon cycle, 4:328*t*–329*t*
  catalysts, 1:308*t*
  centripetal force, 2:50*t*
  chemoreception, 3:304*t*
  childbirth, 3:156*t*
  climate, 4:411*t*
  climax biological communities, 3:407*t*–408*t*
  compounds, 1:279*t*–280*t*
  conservation laws, 2:32*t*
  convection, 4:189*t*–190*t*
  density, 2:25*t*
  diffraction, 2:299*t*
  digestion, human, 3:52*t*–53*t*
  diseases, human, 3:234*t*
  distillation and filtration, 1:359*t*
  Doppler effect, 2:306*t*
  dynamics, 2:19*t*
  Earth, 4:216*t*–217*t*
  Earth-Moon system, 4:81*t*–83*t*
  ecology, 3:367*t*–368*t,* 4:356*t*–357*t*
  economic geology, 4:163*t*–164*t*
  ecosystems, 3:367*t*–368*t,* 4:348*t*–349*t*
  elasticity, 2:153*t*–154*t*
  electromagnetism, 2:351*t*–352*t*
  electrons, 1:90*t*–91t
  elements, 1:124*t*–125*t*
  energy, 4:203*t*–205*t*
  enzymes, 3:29*t*–30*t*
  equilibrium, 2:138*t*
  erosion, 4:271*t*
  evapotranspiration, 4:393*t*–394*t*
  evolution, 3:174*t*–175*t*
  families of elements, 1:145*t*–146*t*
  fluid mechanics, 2:100*t*
  fluid pressure, 2:146*t*
  food webs, 3:74*t*–76*t*
  frame of reference, 2:11*t*
  friction, 2:57*t*
  gas laws, 2:190*t*–191*t*
  gases, 1:57*t*–58*t*
  genetic engineering, 3:124*t*
  genetics, 3:106*t*–108*t*
  geography, 4:50*t*–51*t*
  geologic time, 4:102*t*–103*t*
  geomagnetism, 4:183*t*
  geomorphology, 4:250*t*–251*t*
  geoscience, 4:20*t,* 4:41*t*–42*t*
  glaciology, 4:382*t*–383*t*
  gravity, 2:76*t,* 4:175*t*
  halogens, 1:235*t*
  heat, 2:233*t*–234*t*
  heredity, 3:114*t*
  historical geology, 4:92*t*
  hydrogen, 1:258*t*
  hydrologic cycle, 4:374*t*
  hydrology, 4:367*t*
  immunity and immunology, 3:260*t*
  infectious diseases, 3:251*t*
  instinct, 3:333*t*
  interference, 2:291*t*–292*t*
  ions and ionization, 1:107*t*
  isotopes, 1:99*t*–100*t*
  kinematics, 2:19*t*
  lanthanides, 1:209*t*
  laws of motion, 2:68*t*
  learning and learned behavior, 3:333*t*
  light, 2:363*t*–364*t*
  linear momentum, 2:42*t*–43*t*
  luminescence, 2:370*t*
  machines, 2:168*t*

magnetism, 2:338*t*
mass, density, and volume, 1:29*t*
mass wasting, 4:278*t*–279*t*
measurement, 1:9*t*
metabolism, 3:41*t*–42*t*
metalloids, 1:227*t*
migration, 3:340*t*
minerals, 4:140*t*–141*t*
mixtures, 1:335*t*–336*t*
molecular dynamics, 2:199*t*–201*t*
molecules, 1:114*t*–115*t*
mountains, 4:261*t*–262*t*
mutation, 3:131*t*
navigation, 3:340*t*
nitrogen cycle, 4:336*t*
noninfectious diseases, 3:243*t*
nonmetals, 1:220*t*
organic chemistry, 1:370*t*
oscillations, 2:268*t*–269*t*
osmosis, 1:352*t*
oxidation-reduction reactions, 1:295*t*
paleontology, 4:124*t*–126*t*
parasites and parasitology, 3:280*t*–281*t*
periodic table of elements, 1:137*t*–138*t*
planetary science, 4:69*t*–70*t*
plate tectonics, 4:226*t*–228*t*
polymers, 1:379*t*
precipitation, 4:393*t*–394*t*
pregnancy, 3:156*t*
pressure, 2:146*t*
projectile motion, 2:84*t*
properties of matter, 1:44*t*–46*t*
proteins, 3:22*t*
remote sensing, 4:58*t*
reproduction, 3:139*t*–140*t*
resonance, 2:284*t*
respiration, human, 3:61*t*–62*t*
rocks, 4:151*t*–152*t*
scientific method, 4:10*t*
sediments, 4:289*t*–290*t*
seismology, 4:238*t*–240*t*
sexual reproduction, 3:148*t*–149*t*
soil, 4:298*t*–299*t*
soil conservation, 4:308*t*–309*t*
solar system, 4:81*t*–83*t*
solutions, 1:344*t*–345*t*
species and speciation, 3:212*t*–213*t,* 3:224*t*–225*t*
statics, 2:138*t*
stratigraphy, 4:110*t*–112*t*
succession (biological communities), 3:407*t*–408*t*
sun, 4:81*t*–83*t*
symbiosis, 3:388*t*
systems (physics), 4:29*t*–30*t*
taxonomy, 3:202*t*–203*t*
temperature, 2:242*t*–243*t*
temperature and heat, 1:20*t*–21*t*
thermal expansion, 2:251*t*
thermodynamics, 2:224*t*–225*t*
torque, 2:90*t*
transition metals, 1:193*t*–194*t*
ultrasonics, 2:327*t*
vitamins, 3:94*t*
volume, 2:25*t*
wave motion, 2:260*t*–261*t*
weather, 4:403*t*
Glucose, 3:3–4, 3:56, 3:243
Glycogen, 3:44, 3:*79,* 3:80
God and science. *See* Religion and science
Goddard High Resolution Spectrograph, 2:*342,* 2:350
Goddard, Robert, 2:338
Goiters, 1:*123*
Gold, 1:*182,* 4:138
coinage, 1:187, 1:295
density, 1:*25,* 1:28, 1:30
mining, 4:*19,* 4:161–162
placer deposits, 4:288, 4:290
Goldberger, Joseph, 3:95
Golf, 2:*81,* 2:82
Gondwanaland, 4:220–221
Goodyear Blimp, 2:105, 2:129
Goodyear, Charles, 1:377–378
Gorbachev, Mikhail, 2:178–179
Gordon, John Steele, 1:376–377
Gould, Stephen Jay, 3:177, 4:90–91
GPS (global positioning system), 4:52, 4:*54*
The Graduate (movie), 1:*364,* 1:366
Graf Zeppelin (dirigible), 2:127–128
Grand Canyon, 3:113
Grandfather clocks, 2:267, 2:*272,* 2:274
See also Pendula
Graphite, 1:245–246, 4:139–142, 4:325
Graphs
frame of reference, 2:5–6
statics and equilibrium, 2:134
See also Axes; Coordinates
Grasslands, 3:374–375
Gravitational force, 1:30, 4:169
calculations, 2:75–77
Galilean tests, 2:71
geodesy, 4:171–173
mass *vs.* weight, 1:24–25, 1:30
See also Force; Gravity
Gravity, **2:69–77,** 2:76*t,* **4:169–176,** 4:175*t*
conservation of linear momentum, 2:33
Earth, 4:65–66, 4:214–215
Earth's interior, 4:209–210
Galilean theories, 2:17–18
human cannonballs, 2:*70*
laws of motion, 2:18–20
machines, 2:157
mass wasting, 4:279

projectile motion, 2:78–80
second law of motion, 2:65–66
vacuum, 2:*71*
See also Gravitational force
Great Flood (biblical event), 4:6
Great Lakes (North America), 3:211, 3:354, 4:318
The Great Piece of Turf (painting), 4:15–16
Greek language in chemical symbols, 1:133
Greek thought
causation, 4:3–4
cosmology, 4:64
geography, 4:45–46
geomythology, 4:5–6
See also Aristotelian physics
Greenhouse effect, 3:366, 3:368–369, 4:199
carbon cycle, 4:328–329
ecology, 4:355–356
fossil fuels, 4:201–202
See also Global warming
Greenwich meridian, 2:5
Gregorian calendar, 2:8
Grimaldi, Francesco, 2:296–297, 2:356
Grimm, Jacob, 3:162
Grocery store scanners, 2:*296*
Gross, Hans, 4:20–21
Groundwater
aquifers, 4:373
distribution, 4:387–388
leaching, 4:305–306
soil, 4:294
subsidence, 4:247–248
See also Water
Groups of the periodic table of elements, 1:127, 1:134, 1:135
Guettard, Jean-Etienne, 4:47
Guided missiles, 2:82–85
Gulf of California, 4:*56*
Gulf Stream, 4:364
Gunpowder, 1:292
Guns, Germs, and Steel (Diamond), 4:343
Gurdon, John B., 3:123
Gutenberg discontinuity, 4:213
Gymnosperms, 3:138, 3:140, 3:173–174, 3:*364,* 3:364–365, 4:347–349
Gypsum, 4:138
Gyroscopes, 2:*88,* 2:89–90
Gyroscopic precession, 2:107
See also Gyroscopes
Gyroscopic stability, 2:107
See also Gyroscopes

H

Haber, Fritz, 1:*306*
Habitats and human encroachment, 3:207–209
See also Ecosystems
Habituation (behavior), 3:333
Hachuring, 4:47
Hadean eon, 4:115–116
Haeckel, Ernst von, 3:167, 3:197, 3:391, 4:351
Hafnium, 1:192
Hahn, Otto, 1:199
Hail, 4:392, 4:399, 4:*399*
Haldane, John Scott, 2:124
Halemaumau volcano (Hawaii), 4:5
Halides, 4:134
Halley, Edmund
diving bell, 2:123
Halley's comet, 2:65–66
laws of motion, 2:62
Hall-Héroult process, 1:157, 1:295–296
Halogen lamps, 1:234
Halogens, 1:215, **1:229–236,** 1:235*t*
Handlebars (bicycles), 2:109
Hanging valleys, 4:380
Haploid cells, 3:100
Harden, Sir Arthur, 3:25–26
Hardness of minerals, 4:136, 4:144, 4:156
Hares, 3:226
Harmonic motion
damping, 2:266
Doppler effect, 2:301
electromagnetism, 2:343
frequency, 2:271–274, 2:273–274
resonance, 2:280
wave motion, 2:255
See also Oscillations; Wave motion
Harmonics (acoustics)
frequency, 2:274, 2:276
interference, 2:289
Hartmann, Georg, 4:180
Hartnup disease, 3:15
Harvard University, 2:211
Hauteville, Jean de, 4:234
Hawaiian geomythology, 4:5
Hay fever. *See* Allergies
Hazardous materials and anthrax scare, 3:*250*
HCFCs (hydrochlorofluorcarbons), 1:55, 1:233–234, 2:188
Health, human. *See* Human health
Health or organic foods, 3:86
Heart (human). *See* Circulatory system
Heat, **2:227–235,** 2:233*t*–234*t*
convection, 4:185–186
friction, 2:56
luminescence, 2:366
measurement, 2:219
temperature, 4:193–194
thermal energy, 2:218–219, 2:236–237
transfer, 2:348
See also Temperature; Thermodynamics
Heat capacity, 2:219, 2:230

Heat conduction, 2:220, 2:228
Heat engines, 2:231–232
Heat transfer, 2:220–221, 2:348
  conduction, 2:228
  convection, 2:228–229
  radiation, 2:229
  See also Heat
Heaviside layer, 2:346
Heaviside, Oliver, 2:346
Heavy water, 1:96
Heezen, Bruce Charles, 4:223
Heisenberg, Werner, 1:73–74
Heisenberg Uncertainty Principle, 1:73–74
Helical gears, 2:163
Heliocentric universe, 4:*40*
  frame of reference, 2:9–10
  gravity, 2:70–71
  history, 4:65
  laws of motion, 2:61–62, 2:65
Helium, 1:238, 1:*240,* 1:240–241, 1:242
  balloons and dirigibles, 2:126
  component of universal matter, 1:123
  liquefaction, 2:198, 2:200
  mass to volume ratio, 1:28, 1:36–37
  valence electron configuration, 1:173
Hell, alleged location of, 4:216–218
Helmets, bicycle, 2:109
Helmont, Jan Baptista van, 4:327
Helmont, Johannes van, 1:247
Helsinki University of Technology Low Temperature Laboratory, 2:223
Hemoglobin, 1:301, 3:15–16, 3:19, 3:56, 3:170–171, 4:328
Hemophilia, 3:115–116, 3:241–242, 3:*242*
Hennig, Willi, 3:193
Henry's law, 1:54–55, 2:187
Herbivores
  dinosaurs, 3:184
  food webs, 4:200, 4:342
  place in food web, 3:361
Heredity, 3:99, **3:110–116,** 3:114*t*
  congenital disorders, 3:128–131, 3:*129,* 3:232
  disorders, 3:*113,* 3:121, 3:229, 3:235, 3:240, 3:241–242
  mutation, 3:126, 3:127
Hero of Alexandria, 2:120, 2:163, 2:231
Herodotus (Greek historian), 2:164
Herons, 3:*375*
Herschel, William, 2:349, 4:68, 4:70
Hershey, Alfred, 3:111
Hertz, Heinrich Rudolf
  electromagnetism, 2:341–342
  light, 2:356–357
  wave properties, 2:256–257
Hertz (unit of measure), 2:256–257
Hess, Harry Hammond, 4:222
Heterogeneous equilibrium, 1:299
Heterogeneous mixtures, 1:332, 1:339, 1:354–355
Heterogeneous reactions, 1:286
Hibernation, 3:*40,* 3:40–43
  See also Sleep
Hierarchical behavior (animals), 3:323–324
High Plains Regional Aquifer (U.S.). *See* Ogallala Aquifer (U.S.)
High-level clouds, 4:391
Highways, 3:380
Himalayas (mountain range)
  Mount Machhapuchhare, 4:*246*
  plate tectonics, 4:224
Hindenburg (dirigible), 1:*254,* 1:257, 2:105, 2:126, 2:128
Hindu-Arabic notation system used in measurement, 1:4
Hinnies, 3:215
Hipparchus (Greek astronomer), 4:64
Hiroshima bombardment (1945), 1:72
Histamines, 3:266–267
Historical geology, 3:177, **4:87–94,** 4:92*t,* 4:118
Hittites, 1:190
HIV (human immunodeficiency virus), 3:259
Hockey, 2:54–55
  See also Ice skating
Holmes, Arthur, 4:40
Holmes, Sherlock (fictional detective), 4:20–21
Holograms, 2:*295,* 2:*296,* 2:298–300
Holographic memory, 2:300
Holographic optical elements, 2:299
Homestake Gold Mine (SD), 4:212
Hominidae (family), 3:206
Homo (genus), 3:206
Homo sapiens, 3:206, 3:308
Homo sapiens neanderthalensis, 3:*177*
Homogeneous mixtures, 1:331–332, 1:339–340, 1:354–355
Homogeneous reactions, 1:286
Homosexual community, 3:259
Hooke, Robert, 1:14, 2:148, 2:239
Hooke's law, 2:148
Hooke's scale (temperature), 2:239
Hookworms, 3:278
Hoover bugles, 2:117
Horizontal motion. *See* Projectile motion
Hormones
  amino acids in, 3:13–14
  biological rhythms, 3:307, 3:314–315
  insulin, 3:120, 3:242–243
  therapy, fighting cancer, 3:239
Horsepower (unit of measure), 2:173
Horses, 3:*402*
  domestication, 4:343–344
  fossil record, 3:172–173

mating with donkeys, 3:215
species, 3:222
Hospitals, 3:154
Hot-air balloons, 1:55–56, 2:126, 2:*186,* 2:188
See also Balloons
Hot extrusion of metals, 2:151
Hot spots (geology), 4:258
Houot, Georges, 2:125
Housing, 1:*154*
Howard, Luke, 4:390–391
Hubble, Edwin, 2:307, 2:358
Hubble Space Telescope, 2:*342,* 2:350
Human behavior
competition, 3:393
fighting, 3:325–326
learning, 3:331–334
operant conditioning, 3:320–321
symbiotic relationships, 3:383, 3:386–387
Human body
acids and bases, 1:315
carbon content, 4:325
elements in, 3:348
nitrogen content, 4:333
nonmetals, 1:216
saltwater, 1:350
transition metals, 1:186
Human cannonballs, 2:*70*
Human Genome Project, 3:103–104, 3:118, 3:120–121
Human health, 1:124–126, 1:177
causes of death in U.S., 3:231, 3:236
impact of nuclear radiation, 3:73
impact of obesity, 3:39–40
nutrition, 3:8–10
presence of proteins, 3:20–23
See also Diseases, human
Human history and development
causing ecological disturbances, 3:403
early civilizations, 3:186, 3:353, 3:395–396
early migrations, 3:162–163
ecosystems, 4:342–345
encroaching on animal habitats, 3:207–209
evolution of primates, 3:167–169, 3:*177,* 3:220–221
first *Homo sapiens,* 3:181, 3:308
geologic time, 4:93–94
ice ages, 4:382–384
mass extinctions, 4:127
Human immunodeficiency virus (HIV), 3:259
Human intelligence, 3:168, 3:333
Human sexuality, 3:145–149, 3:*146*
Humason, Milton, 2:307
Humboldt, Alexander von, 1:78–79
Hume, David, 3:167
Humus, 4:*295*
Huns, 3:163
Hunting of endangered species, 3:208
Huntington disease, 3:128
Hurricane Andrew (1989), 4:400–401
Hurricane Hugo (1989), 4:400
Hurricanes, 4:400–402, 4:*401*
See also Natural disasters
Hutton, James, 3:177, 4:27, 4:39, 4:90, 4:91
Huygens, Christiaan
pendulum clocks, 2:267, 2:274
wave theory of light, 2:296, 2:343, 2:355–356
Hyatt, John Wesley, 1:377
Hybridization (genetics), 3:110
Hydraulic presses, 2:167–169
fluid mechanics, 2:98–99
origins, 2:160
Pascal's principle, 2:142–143
Hydraulic rams. *See* Hydraulic presses
Hydrocarbon derivatives, 1:368–369, 1:375
Hydrocarbons, 1:256–257, 1:367–368, 1:373–374, 1:375, 3:178, 4:157–158
Hydrochloric acid, 1:231, 1:256
Hydrochlorofluorocarbons (HCFCs), 1:55, 1:233–234, 2:188
Hydrodynamica (Bernoulli), 2:113, 2:195
Hydrodynamics, 2:96–97
See also Dynamics
Hydroelectric dams
conservation of energy, 2:176
fluid mechanics, 2:101
Hydrofluoric acid, 1:232
Hydrogen, **1:252–259,** 1:258*t*
alternative energy, 4:202
in amino acids, 3:11–13
atomic structure, 1:142–143
balloons and airships, 1:*254,* 2:105, 2:126–128
bonding, 1:*265*
component of universal matter, 1:123
infrared astronomy, 2:350
isotopes, 1:95–97
liquefaction, 2:200
percentage of biosphere, 3:348
percentage of human body mass, 3:78
Hydrogen bombs, 1:*93,* 1:97, 1:255, 2:177–179
See also Nuclear weapons
Hydrogen chloride, 1:256
Hydrogen fuel, 1:259
Hydrogen peroxide, 1:109, 1:256
Hydrogen sulfide, 1:256, 3:54, 4:320–321
Hydrogenation, 3:36
Hydrologic cycle, 3:347–348, **4:369–375,** 4:374*t*
evapotranspiration, **4:387–394**
hydrology, 4:361–362
precipitation, **4:387–394**
weather, 4:396
Hydrology, 4:43, **4:361–367,** 4:367*t*
hydrologic cycle, **4:369–375**

whirlpools, 4:*363*
See also Earth sciences; Water
Hydrolysis, 3:14
Hydrosphere, 3:346
geoscience, 4:26–27
hydrologic cycle, 4:369–370
hydrology, 4:361–362
See also Water
Hypersomnia, 3:310
Hypersonic flight. *See* Supersonic flight
Hypersound, 2:313
Hypoteneuse. *See* Trigonometry
Hypotheses. *See* Scientific method
Hyracotherium (early horse ancestor), 3:172
Hyraxes, 3:222

I

I-hsing, 2:267
Ibn al-Haytham, 2:342, 2:354
Ibn Bâjja, 2:61
Ibn Sina, 2:61
ICBMs. *See* Intercontinental ballistic missiles (ICBMs)
Ice
buoyancy, 2:*123*
characteristics, 2:208
floating characteristics, 2:*204*
glaciology, 4:376–377
sedimentation, 4:285
snowflakes, 4:*392*
thermal expansion, 2:*247,* 2:248–249, 2:249
See also Glaciers; Water
Ice ages
climate, 4:411–412
glaciology, 4:381–384
Ice caps, 4:378, 4:379–380
Ice domes, 4:378
Ice fishing, 2:*247*
Ice sheets, 4:378–379
Ice shelves, 4:*377,* 4:379
Ice skating, 2:27, 2:33
See also Hockey
Icebergs, 2:*204*
Iconometry. *See* Photogrammetry
Ideal gas law, 1:53, 2:185
Igneous rocks, 4:148–149
Ileum, 3:47
Immune system, **3:262–269,** 3:266*t*–267*t*
AIDS, 3:245, 3:250, 3:258–261
autoimmune diseases, 3:230, 3:242
fighting infectious diseases, 3:244–245
Immunity and immunology, **3:255–261,** 3:260*t*
Immunotherapy, 3:239
Imprinting (behavior), 3:322–323, 3:328–329, 3:*329,* 3:333–334
Impulse (force)
collisions, 2:41–44
linear momentum, 2:39–40
In vitro fertilization, 3:144, 3:*144*
Inbreeding, 3:115–116
Incandescent bulbs, 2:360–361, 2:*367,* 2:369
Incendiary devices, 1:175–176
Incest, 3:116
Inclined planes, 2:164–165
Galilean tests, 2:18, 2:71
origins, 2:159
screws, 2:165–167
wedges, 2:165
Index cards and Bernoulli's principle, 2:119
Indian pipe (plant), 3:385
Indian vaccine research, 3:256
Indicator species, 3:71–72, 3:392, 4:352
Indigestion, 3:48
Indigo, 2:355
Indium, 1:157–158
Indo-European development, 3:162
Induced drag, 2:106
See also Drag
Induction, electromagnetic, 2:341
Industrial distillation, 1:357–358
Industrial melanism, 3:173
Industrial minerals, 4:162, 4:164–165
Industrial Revolution, 3:173, 3:240
Industrial uses
genetic engineering, 3:119
lactic acid in food production, 3:59–60
minerals, 4:162, 4:164–165
nighttime activity, 3:312
Industrialized nations
causes of death, 3:231
deforestation, 3:365–366
Inelastic collisions, 2:40–44
Inert gases. *See* Noble gases
Inertia
cars, 2:62–63
centripetal force, 2:46–48
first law of motion, 2:18–19, 2:62–65, 4:171
frame of reference, 2:9–10
friction, 2:52–53
Galilean observations, 2:62
gravity, 2:72
linear momentum, 2:37
tablecloths, 2:63–64
See also First law of motion; Momentum
Inertial navigation systems, 2:64
Infection, **3:283–291,** 3:289*t*–290*t*
Infectious diseases, **3:244–252**
ecosystems, 4:344–345
glossary, 3:251*t*

parasites, 3:278
plague, 3:230
relation to cancer, 3:240
See also Diseases, human
Infiltration in hydrologic cycle, 4:372–373
Inflation, monetary, 1:*4,* 1:6
Influenza, 3:60
caused by virus, 3:287
epidemic 1918-1920, 3:249–250
Infradian cycles, 3:313
Infrared light, 2:349–350, 2:357–358
Infrared photography, 2:349–350, 4:54
Infrasound, 2:313
Inhibition model (biological communities), 3:401–402
Innate behavior, 3:319–320, 3:322, 3:328
Inner ear, 2:317–318
Inorganic compounds, 1:276
Inorganic substances. *See* Organic substances
Inquilinism, 3:384
Insecticides. *See* Pesticides
Insectivores, 3:219–220
Insects
ants, 3:*349,* 3:386, 3:388–389
aphids, 3:388
bedbugs, 3:281–282
bees, 3:211, 3:*211,* 3:303–304, 3:323–324
butterflies, 3:338, 3:388–389
class Insecta, 3:275
evolution, 3:165
fleas, 3:282
infectious diseases, 3:245
lice, 3:282
locusts, 3:*405*
moths, 3:138, 3:173
parasites, 3:279–282
respiration, 3:57
symbiotic relationships, 3:386, 3:388–389
taxonomy, 3:200, 3:275
termites, 3:6, 3:*6*
ticks, 3:*279,* 3:282
Insomnia, 3:310
Instinct, **3:327–334,** 3:333*t,* 3:335
See also Behavior; Learning and learned behavior
Insulin, 3:120, 3:242–243
Intelligence, 3:168
Intelligent design theory, 3:168–169
Intercontinental ballistic missiles (ICBMs), 2:82
Interference (wave mechanics), **2:286–293,** 2:291*t*–292*t,* 2:356
Intermolecular bonds, 1:47, 1:113–114
hydrogen, 1:253–254
metals, 1:151
minerals, 4:131–132
International Prototype Kilogram, 2:8
International System of Units, 1:7. *See also* Metric system
International Ultraviolet Explorer, 2:350
International Union of Pure and Applied Chemistry (IUPAC). *See* IUPAC (International Union of Pure and Applied Chemistry)
Interstate-285 (Atlanta, GA), 2:45–46
Intervals (music), 2:274, 2:276
Intestinal gas, 3:54
Intrinsic diseases, 3:229
Introduced species, 3:209–214
Intromission, 2:342, 2:354
Inuit, 3:*207*
Invisible fences, 2:323
Iodine, 1:234, 1:236
Ion exchange, 1:106
Ionic bonding, 1:268
carbon, 1:364
metals, 1:151
octet rule, 1:103–104
valence electrons, 1:113
Ionic compounds, 1:104
Ionization energy, 1:104–105
Ionizing radiation, 1:106, 1:108, 2:365
See also Ionosphere; Radiation (electromagnetism)
Ionosphere, 2:346
Ions and ionization, 1:35, 1:84, **1:101–108,** 1:107*t,* 1:121
chemical bonding, 1:267
static electricity, 1:*102*
Iranian earthquake (1755), 4:237
Iraqi desertification, 4:307–308
Iridium, 1:191, 3:185
Iron, 1:190, 1:336, 2:332
mass to volume ratio, 1:28, 1:36–37
rust, 1:285
Iron lung, 3:287
Iron ore mines, 1:*183*
Iron ore smelting, 1:190
Irruptive migration, 3:336
Islam, 3:246
Islands, 4:*249*
biogeography, 3:402–403
continental islands, 4:249–250
ecosystems, 4:251–252
geomorphology, 4:248–252
hot spots, 4:258
oceanic islands, 4:250–251
Isomers, 1:278
Isostatic compensation, 4:248
Isotopes, 1:35, **1:92–100,** 1:99*t*–100*t,* 1:120–121, 4:74
actinides, 1:197
atomic mass, 1:65, 1:130
carbon, 1:243
hydrogen, 1:252

identified, 1:71
periodic table of elements, 1:81
uranium, 1:201
used in radiometric dating, 3:172
IUPAC (International Union of Pure and Applied Chemistry)
naming conventions for elements, 1:133
periodic table of elements, 1:134, 1:140–141
transition metals, 1:182–183

J

Jakob, Alfons Maria, 3:232–233
Janssen, Pierre, 1:238
Jar lids and thermal expansion, 2:250
Jejunum, 3:47
Jellyfish, 3:*321*
Jenner, Edward, 3:255–257, 3:*257*
Jet engines, 2:*312*
Jet lag, 3:310–311
Jewels, 4:165
Jews, 3:*121*
Johannes Philoponus, 2:61
Johnson, Earvin "Magic," 3:259–261
Johnson, Paul, 2:10–12
Joint Institute of Laboratory Astrophysics (Boulder, CO), 2:211
Jolbert, Domina, 2:108
Jones, Indiana (fictional archaeologist), 4:17
Joule, James, 2:230
Joule (unit of measure), 2:219, 2:229, 2:345
Journey to the Center of the Earth (novel), 4:215–216
Jovian planets, 4:210
Julian calendar, 2:8
Junk food, 3:10, 3:79
Jurassic Park (movie), 3:184, 4:17
Justinian I (Roman emperor), 4:31

K

Kaiko (unmanned underwater vessel), 2:124–125
Kangaroo rats, 3:329–330
Kangaroos, 3:219, 3:*219*
Kaposi's sarcoma, 3:258, 3:*259*
Karate chops, 2:140
Karst topography, 4:247, 4:366–367
Kekulé, Friedrich August, 1:265–267
Kelp forests, 3:71
Kelvin, Lord. *See* Thomson, William, Lord Kelvin
Kelvin scale, 2:184, 2:197
Kelvin temperature scale, 1:15–16, 1:52
Kennelly, Arthur Edwin, 2:346
Kennelly-Heaviside layer, 2:346
Kennicott Glacier (AK), 4:*381*
Kepler, Johannes, 4:*66*
laws of planetary motion, 2:71–72, 4:65
telescopes, 2:354
Ketoacidosis, 3:243
Ketones, 1:369
Kettle lakes, 4:380
Kettlewell, Bernard, 3:173
Kevlar, 1:*375*
Keys, David, 4:31
Keystone species, 3:69–71, 3:*70*
Kidney dialysis, 1:*350,* 1:351
Kilocalorie (unit of measure), 2:219, 2:229
Kilograms, 1:9
Kilohertz (unit of measure), 2:256–257
Kilowatt (unit of measure), 2:173–174
Kinematics, **2:13–20,** 2:19*t*
Kinetic energy, 1:11–12, 4:23–24
Bernoulli's principle, 2:112
conservation, 2:28–29
conservation in elastic collisions, 2:41
falling objects, 2:174–175
formula, 2:29, 2:174
frequency, 2:271
heat, 2:227–228
molecular dynamics, 2:195
oscillations, 2:265–266
resonance, 2:279
roller coasters, 2:50
thermal expansion, 2:245
thermodynamics, 2:217–218
See also Energy
Kinetic theory of gases, 1:53–54
Kinetic theory of matter
Brownian motion, 1:69
gases, 2:196–197
molecular dynamics, 2:195–197
Kingdoms (taxonomy), 3:198–200
Kipfer, Paul, 2:126–127
Kircher, Athanasius, 3:288
Kirchhoff, Gottlieb, 1:306, 3:25
Kites, 2:107–108, 2:*114,* 2:116
Kleine-Levin syndrome, 3:310
Knives, 2:165
Knoop scale, 4:156
Knuckle balls, 2:81–82
Ko Yu, 2:162–163
Köppen, Wladimir, 4:407
Korean Air Lines Flight 007 shootdown (1983), 2:64
Kotler, Kerry, 3:108–109
Krakatau (Indonesia)
eruptions, 4:259–260
meteorological effects, 4:31
Krebs cycle, 3:34–35
Krebs, Sir Hans Adolf, 3:34–35
Kronland, Johannes Marcus von, 2:296
Krypton, 1:241

Kudzu, 3:211–214, 3:274, 4:279–280
Kwashiorkor, 3:85

L

La Mettrie, Julien de, 4:90
Labels, food, 3:79
Labor (birth), 3:153
Laborers
  diseases, 3:240, 3:*240*
  forced labor, 3:366
Lactic acid, 3:59
Lactose, 3:4
Lactose intolerance, 3:27
Laden, Osama bin, 4:19–20
Lagomorphs, 3:224–226
Lake Erie, 3:354, 4:318
Lake Victoria (Africa), 3:210
Lakes
  biomes, 3:375–376
  eutrophication, 3:354
  introduced species, 3:210–211
Lamarck, Jean Baptiste de, 3:165, 3:197
Laminar flow
  aerodynamics, 2:102–103
  airplanes, 2:105–106
  Bernoulli's principle, 2:113–115
  See also Airflow
Lamps, 2:360–361
Landforms (geomorphology), 4:245–247
Landsat (satellite program), 4:57, 4:59
Lange, Dorothea, 4:304
Language used in chemical symbols, 1:122–123, 1:132–133
Languages, 3:162
Lanterns, 2:360–361
Lanthanide contraction, 1:207
Lanthanides, 1:155–156, **1:205–210,** 1:209*t*
  electron configuration, 1:136
  orbital patterns, 1:144, 1:146, 1:185–186, 1:197
Lanthanum, 1:208
Laplace, Pierre Simon de, 2:230, 4:90
Large intestine, 3:47
Las Vegas (NV), 1:*239*
Laser etching, 2:364
Lasers, 2:361–362, 2:363
  fluorescence, 2:369
  holograms, 2:298–300
Lasky, Melvin J., 4:263
Lates niloticus, 3:210
Latin used in element names, 1:122–123
Laue, Max Theodor Felix, 2:297
Laurasia, 4:220
Laussedat, Aimé, 4:53–54
Lava, 4:*148*
Lava domes, 4:258
Laval, Carl de, 2:49
Lavoisier, Antoine, 1:68, 1:112, 2:230
Law of chemical equilibrium, 1:299–300
Law of universal gravitation, 4:170–171
Laws of conservation. *See* Conservation laws
Laws of friction, 2:52–54
Laws of motion, 2:18–20, **2:59–67,** 2:68*t*
  gravity, 4:171
  molecules, 2:206
  potential and kinetic energy, 2:174
  torque, 2:86
  See also Conservation of angular momentum; Conservation of linear momentum; First law of motion; Laws of planetary motion; Motion; Second law of motion; Third law of motion
Laws of planetary motion, 2:71–72, 4:65
  See also Laws of motion
Laws (Science). *See* Scientific method; *specific laws*
Laws of thermodynamics, 2:216–217, 2:221–223, 4:194–195
Le Châtelier's law, 1:19, 1:300
Leaching, 4:292
  nitrogen cycle, 4:338
  soil conservation, 4:305–306
  See also Groundwater
Lead, 1:158, 4:139
Learning and learned behavior, 3:319–320, 3:322, **3:327–334,** 3:333*t*
  See also Behavior; Instinct
Leaves, 4:*295*
Lebanon, Kansas, 2:137
Leewenhoek, Anton van, 3:*288*
Left-hand or right-hand amino acids, 3:13, 3:17
Legality of teaching evolution, 3:169
Lehmann, Johann Gottlob, 4:39, 4:88, 4:105
Leibniz, Gottfried Wilhelm, 2:300
Leks (animal territory), 3:324
Lemaître, Georges Édouard, 4:71
Lemons, 3:93
Lemurs, 3:220
Length (measurement), 1:23, 2:21
Lentic biomes, 3:375–376
Leonardo da Vinci, 2:360, 4:*89*
  fossils, 4:88, 4:105
  geology, 4:39
Leprosy, 3:248–249, 3:*249*
Leptons, 1:66
Leucippus, 1:67, 2:14
Lever arm. *See* Moment arm
Levers, 2:160–162
  classes, 2:161–162
  mechanical advantage, 2:*158*
  origins, 2:159
  pulleys, 2:164

wheels and axles, 2:162–164
See also Torque
Lewis, Gilbert Newton, 1:268, 1:*320*
Lewis structure, 1:268–269
Lewis's acid-base theory, 1:313, 1:321
Liang Ling-tsan, 2:267
Libraries and taxonomy, 3:194
Lice, 3:282
Lichen, 3:386
Lids and thermal expansion, 2:250
Life on Mars, 4:384
Lift (aerodynamics)
airplanes, 2:105–106
birds, 2:104–105
cars, 2:109–110
Lift coefficient, 2:105–106
Light, **2:354–364,** 2:363*t*–364*t*
artificial light, 3:311–312, 3:*312*
Bose-Einstein Condensate, 2:211
electromagnetism, 2:349–350
luminescence, 2:366–367
source, 2:342
See also Corpuscular theory of light; Sunlight
Light amplification by stimulated emission of radiation. *See* Lasers
Light bulbs, 2:360–361, 2:*367,* 2:369
Light spectrum, 2:354–355
diffraction, 2:296–297
luminescence, 2:366–367
rainbows, 2:358–359
Light waves
diffraction, 2:295–296
Doppler effect, 2:305, 2:307
frequency, 2:276
reflection, 2:259
resonance, 2:282
See also Waves
Lighthouses, 2:297
Lightning, 4:398
Lilac, 3:*355*
Limes, 3:93
Lincoln, Abraham, 2:121–122, 3:114–115
Lind, James, 3:93
Lindbergh, Charles, 2:127–128
Linear momentum, 2:37–44
airbags, 2:43
baseball, 2:*40,* 2:44
conservation, 2:30–31, 2:33, 2:38–39
glossary, 2:42*t*–43*t*
mass, 2:37–38
relationship to inertia, 2:37
second law of motion, 2:65
skydiving, 2:*39,* 2:43–44
Superman (fictional superhero), 2:44
water balloons, 2:44
See also Conservation of linear momentum; Momentum
Linear motion, 2:16–18
See also Motion
Linnaean system, 4:118–119
Linnaeus, Carolus, 3:197, 3:205, 4:118
The Lion King (movie), 4:64
Lipids, 3:44–45
importance in nutrition, 3:80
metabolism, 3:35
in proteins, 3:19
Liquefaction, 2:198, 2:200–201
Liquefied gases, 1:43
Liquefied natural gas (LNG)
containers, 2:*193*
usage, 2:200–201
Liquefied petroleum gas (LPG), 2:200–201
Liquid crystals, 1:43, 2:212, 2:214
See also Crystals; Liquids
Liquid filtration, 1:358
Liquid nitrogen, 1:*214,* 4:*332*
Liquids, 1:39
acoustics, 2:312, 2:321
behavior, 2:183
boiling, 2:209
characteristics, 2:148
evaporation, 2:208–209
liquid crystals, 2:212, 2:214
melting, 2:208
molecular behavior, 2:95–96
properties, 1:49*t*
thermal expansion, 2:248–249
triple point, 2:6
volume measurement, 1:27–28, 2:23–24, 2:24
Lisbon earthquake (1755), 4:233–234
Listening devices, 2:*322*
Lister, Joseph, 3:290
Lithium, 1:164–166, 3:302
Lithium batteries, 1:*163,* 1:164–165
Lithosphere
convection, 4:188
plate tectonics, 4:229
structure, 4:212–213
Lithostratigraphy, 4:106
Litmus paper, 1:314
Little Ice Age (1250-1850), 4:384
Liver, human, 3:*79,* 3:91–92
Living organisms and carbon, 1:243
Llamas, 4:*344*
LNG. *See* Liquefied natural gas
Loa loa, 3:279
Lobsters, 3:*171*
Lockyer, Sir Joseph, 1:238
Locusts, 3:*405*
Loggerhead turtles, 3:338–339

Logging and forestry, 3:363, 3:365–366, 3:403, 3:406, 3:407–408
Lohmann, Kenneth, 3:339
Loma Prieta (CA) earthquake (1989), 4:235
  damage, 4:*236*
  seismograph reading, 4:*233*
London dispersion forces, 1:47, 1:114–115
Long, Huey P., 4:365–366
Longitude, 2:*5,* 4:51–52
  See also Prime meridian
Longitudinal waves, 2:257–258
  frequency, 2:272–273
  ultrasonics, 2:320
  See also Waves
Lord Kelvin. *See* Thomson, William, Lord Kelvin
Lord Rayleigh, 1:238–239, 2:358, 4:232
Lordosis (behavior), 3:330
Lorenz, Edward, 4:24–25, 4:404
Lorenz, Konrad, 3:320, 3:322–323, 3:325–326, 3:327, 3:328–329
Los Angeles (CA) geomorphology, 4:18
Lotic biomes, 3:375–376
Loudspeakers
  acoustics, 2:315, 2:320–321
  magnetism, 2:336
Love, Augustus Edward Hough, 4:232
Love waves, 4:232–233
Lovelock, James, 4:27
Low-density lipoproteins, 3:36–37
Low-level clouds, 4:391
Loxodonta africana, 3:200
Loxodonta cyclotisare, 3:200
LPG (liquefied petroleum gas), 2:200–201
LSD (lysergic acid diethylamide), 3:307
Lubrication, 2:56
Lucretius (Roman philosopher), 1:263
Lucy *(australopithecus),* 3:216
Luminescence, **2:365–371,** 2:370*t*
Luminol, 3:21
Lunar cycle. *See* Moon
Lung cancer, 3:62
Lungs, 3:57–58, 3:*59*
  See also Respiration
Lupus (systemic lupus erythematosus), 3:268
Lutetium, 1:210
Luxury taxes, 4:27–28
Lye, 1:317–318
Lyell, Charles, 4:90, 4:91
Lymph nodes, 3:263
Lymphocytes, 3:255, 3:263, 3:*263,* 3:264

M

MacArthur, R. H., 3:402
Mach numbers
  airplanes, 2:106–107
  Doppler effect, 2:305
Machine efficiency, 2:159
  friction, 2:55–56
  thermodynamics, 2:216–218
  See also Machines
Machines, **2:157–169,** 2:168*t*
  See also Force; Machine efficiency; Mechanical advantage; Work
Mackenzie, D. P., 4:222–223
MacLeod, Colin Munro, 3:111
Macroscelideans, 3:224–226
Mad cow disease, 3:233
Madagascar, 3:138, 4:*353*
MAGLEV trains, 2:337–339
Magnesium, 1:*172,* 1:175
Magnetic compasses, 2:334–335, 4:180
Magnetic levitation trains, 2:337–339
Magnetic metals, 1:190–191, 2:331–332
Magnetic poles
  bar magnets, 2:334
  Earth, 2:334–335, 3:338–339
  electromagnets, 2:334
  repulsion, 2:337–338
Magnetic repulsion, 2:337–338
Magnetic resonance imaging, 2:335–336, 3:*237*
Magnetic tape, 2:336–337
Magnetism, **2:331–339,** 2:338*t,* 4:179–180
  laws, 2:340–341
  magnetic fields, 4:*178*
  recording devices, 2:*332,* 2:*333*
  See also Antiferromagnetism; Diamagnetism; Ferrimagnetism; Ferromagnetism; Geomagnetism; Paramagnetism
Magnetometers, 2:335
Magnetorestrictive devices, 2:322
Magnetosphere, 4:181
Magnetron, 2:348
Magnets
  ferromagnetism, 2:332–334
  magnetic fields, 2:332, 4:*178*
  natural magnets, 2:331–332
  See also Bar magnets; Electromagnets; Magnetism
Maiman, Theodore Harold, 2:369
Main-group elements. *See* Representative elements
Major histocompatibility complex, 3:262–263
Malaria, 3:249, 3:276–277
Male reproductive system, 3:142–143
Mallet, Robert, 4:234
Mallon, "Typhoid" Mary, 3:251
Malnutrition, 3:82–86, 3:89
Maltose, 3:4
Mammals
  class mammalia, 3:205, 3:218–226

evolutionary history, 3:195, 3:204–205, 3:217–218
respiration, 3:58
Management of natural resources, 3:363
Manganese, 1:194
Mangrove forests, 3:*362,* 4:346
Manhattan Project, 1:72, 1:97, 1:199–200, 2:177
Manic depression, 1:165
Mantle (Earth). *See* Asthenosphere
Mantophasmatodea, 3:200
Manx shearwaters (bird), 3:338
Mapmaking, 4:45, 4:46
Maps
geography, **4:44–52**
geologic maps, 4:44, 4:47–49
historical map of world, 4:*16*
Mercator projection of Earth, 4:*46*
relief map of Earth, 4:*48*
See also Cartography
Marconi, Guglielmo, 2:342, 2:345
Marfan syndrome, 3:114–115
Margulis, Lynn, 4:27
Mariana Trench, 2:124–125
Marignac, Jean-Charles Galissard de, 1:208–209
Marine animals and phosphorescence, 2:369–370
Marrow (bone), 3:263, 3:*263*
Mars (planet)
balloon exploration, 2:129
life, 4:384
Phobos, 4:*174*
planetary science, 4:66
roundness, 2:76–77, 4:173–174
Marsupials, 3:218–219, 3:*219*
Mason, Charles, 4:47
Mason-Dixon Line, 4:47
Mass, **1:23–30,** 1:29*t*
centripetal force, 2:46–47
definition, 2:21–22
gravity, 2:72–74, 4:173
laws of motion, 2:18–20
linear momentum, 2:37–38
measurement, 2:21
second law of motion, 2:65
weight vs., 1:76
See also Weight
Mass energy. *See* Rest energy
Mass extinctions, 4:123, 4:126–127
Mass movement (geology). *See* Mass wasting
Mass number, 1:65
Mass spectrometry, 1:80–81, 1:106
Mass wasting, **4:273–280,** 4:278*t*–279*t,* 4:284
Matches, 2:*54,* 2:56
Material causes (philosophy), 4:3–5
Material processing and ultrasonics, 2:325–326
Mathematical Principles of Natural Philosophy (Newton). *See Principia*
Mathematics, 2:14, 2:18
Mating rituals
animal, 3:*145,* 3:145–147
human, 3:145
pheromones, 3:304
Matter, 1:44*t*–1:46*t,* **2:203–215**
definition, 2:21–22
molecular dynamics, 2:195
phases, 2:14, 2:22, 2:197–198
properties, **1:33–47,** 1:49*t*
See also Phases of matter
Maxwell, James Clerk, 4:178–179
electromagnetism, 2:20, 2:157, 2:207, 2:341, 2:356–357
kinetic theory of matter, 2:206
molecular dynamics, 2:194, 2:196
thermal expansion, 2:245–246
Mayer, Julius Robert, 2:222
Mayr, Ernst, 3:206
McCandless, Bruce, 4:*215*
McCartney, Paul, 2:323
McCarty, Maclyn, 3:111
M-discontinuity, 4:213, 4:240–241
Measurements, **1:3–10,** 1:9*t,* 2:7–9
air pressure, 2:183
calibration, 2:8
establishment, 2:8
latitude and longitude, 2:7–8
metric system *vs.* British system, 2:8–9
standards, 2:21
temperature and heat, 1:17
value to societies, 2:8
See also English measurement system; Metric system
Meat
preservation, 1:351–353
protein content, 3:23
red meat in diet, 3:49–50
undercooked meat, 3:277–278, 3:303
See also Carnivores
Mechanical advantage, **2:157–169,** 2:168*t*
See also Machines
Mechanical deposition, 4:287
Mechanical energy
conservation, 2:28–29
kinetic and potential energy, 2:174–177
thermodynamics, 2:217–218
See also Energy
Mechanical waves
interference, 2:289
properties, 2:256
See also Waves
Mechanical weathering, 4:264
Mechanics (physics)
classical physics, 2:20
machines, 2:158–160

Mechanist school, 3:167
Medical treatments and research
bacteriology, 3:288, 3:290
brain, 3:234
cancer, 3:239
childbirth, 3:155–157
cloning cells, 3:123
designer proteins, 3:21
genetic engineering, 3:103, 3:120, 3:122–123
immunology, 3:255–261
in vitro fertilization, 3:144
insulin, 3:120, 3:243
lithium, 1:165
ultrasonics, 2:324
use of amino acids, 3:15
x-rays, 2:350, 2:352
Medicines. *See* Drugs and medicines
Megahertz (unit of measure), 2:256–257
Meiosis, 3:100, 3:136
Meitner, Lise, 1:199
Melanin, 3:130–131, 3:173
Melatonin, 3:307, 3:314–315
Melting, 2:207–208
Melting points
alkali metals, 1:163–164
alkaline earth metals, 1:173
water, 1:38
Memoire sur la diffraction de la lumiere (Fresnel), 2:297
Mendel, Gregor, 3:110–111
Mendeleev, Dmitri, 1:69, 1:127, 1:128–130
Menstruation, 3:286, 3:313
Mercalli scale, 4:234–235
Mercator, Gerhardus, 4:46
Mercator projections, 4:*46*
Mercury (element), 1:189–190
barometers, 2:141
thermometers, 1:16, 1:189, 2:250–251
thermometric medium, 2:242
Merychippus (horse ancestor), 3:173
Mesosphere, 214
Mesozoic era, 3:183–184, 4:108, 4:117–118
Metabolic enzymes, 3:27
Metabolism, **3:33–43**
disorders, 3:37–38
glossary, 3:41*t*–42*t*
Metalloids, 1:147, **1:222–228,** 1:227*t*
Metals, **1:151–161,** 1:*152,* 1:159*t*–160*t*
cations, 1:103
conductivity, 2:228
crystals, 2:151–152
elasticity, 2:150–151
families of elements, 1:147
ferromagnetism, 2:332–334
housing, 1:*154*
metalloids, 1:222–223
microwave resonance, 2:283, 2:348
rust, 1:*283*
Metamorphic rocks, 4:150, 4:*150,* 4:152–153
Metchnikoff, Élie, 3:255
Meteor Crater (AZ), 4:*91*
Meteorites, 3:345
cause of mass extinction, 3:185–186, 3:*186*
life on Mars, 4:384
Meteor Crater (AZ), 4:*91*
See also Asteroids
Meteorological radar, 2:*303,* 2:305
Meteorology, 4:402–404, 4:406–407
See also Weather
Meters, 1:9
Methane produced by ruminants, 3:7–8
Metric system, 1:7–8
Celsius temperature scale, 1:15
comparison to British system, 2:8–9
establishment, 2:8
gravity, 2:72–74
pressure measurements, 1:50
See also Measurements
Metronomes, 2:267, 2:274
Mettrie, Julien de La, 3:167
Meusnier, Jean-Baptiste-Marie, 2:126–127
Mexico City Olympics (1968), 2:146
Mica, 4:*150*
Mice, 3:123, 3:163–164, 3:226
Michell, John, 4:233–234
Microclimates, 4:407–409
Central Park (New York, NY), 4:*410*
sand dunes, 4:*407*
Microphones, 2:336
Microscopes, 3:*288*
Microwave ovens, 2:348
Microwaves
communications, 2:347–348
frequency, 2:276–277
ovens, 2:348
radar, 2:348–349
resonance, 2:282–283
Mid-level clouds, 4:391
Mid-ocean ridges, 4:*221,* 4:222–223, 4:257
See also Rift valleys
Middle Ages
bestiaries, 3:*196*
plague (1347-1351), 3:247–248
Middle C, 2:*273,* 2:274
Middle ear, 2:317
Midgets, 3:129
Midwives, 3:153–154
Miescher, Johann Friedrich, 3:111, 3:117
Migration
animal behavior, **3:335–341**
early humans, 3:162
glossary, 3:340*t*

Milankovitch, Milutin, 4:411
Military research into remote sensing, 4:53–54
Milk, 1:*177*
Milky Way (galaxy), 2:211, 4:*67,* 4:70–71
Millbrae (CA) mudflows, 4:*276*
Miller, Stanley, 3:179
Milligal (unit of measurement), 4:172
Mills, 2:163
Milne, John, 4:234
Mineraloids, 4:135
Minerals, **4:129–142,** 4:140*t*–141*t*
  applications, 4:165
  deposits, 4:288, 4:290–291
  economic geology, 4:155–156
  evaporites, 4:290–291
  groups, 4:145
  identification, 4:144–145
  importance in nutrition, 3:80–81
  jewels, 4:165
  rocks, 4:143–145
  serpentine, 3:71
  soil, 4:294
Minié, Claude-Etienne, 2:80
Mining, 1:*183*
  economic geology, 4:161–162
  gold mines, 4:*19*
  subsidence, 4:248
Minnows, 3:327–328
Mirages, 2:359
Mirrors, 2:361
Miscarriage, 3:152–153
Misch metal, 1:*206,* 1:208
Miscibility, 1:340
Mississippi River flooding, 4:*365,* 4:365–366
Mitosis, 3:99–100, 3:135
Mixtures, **1:329–337,** 1:335*t*–336*t,* 1:354–355
  compounds vs., 1:*274,* 1:275, 1:338–339
  distillation, 1:355–358
  filtration, 1:358–359, 355
  minerals, 4:131
  solutions, 1:338–339
Mobility (mammals), 3:198, 3:218
Modern physics, 2:20, 2:56
  See also Physics
Mohave Desert, 3:*351*
Moho (Mohorovicic discontinuity), 4:213, 4:240–241
Mohorovicic, Andrija, 4:213, 4:240–241
Mohorovicic discontinuity, 4:213, 4:240–241
Mohs, Friedrich, 4:136, 4:144
Mohs scale, 4:136, 4:144, 4:156
Moissan, Henri, 1:232
Molar mass, 1:26–27, 1:36, 1:81–82
Molarity, 1:340
Molecular dynamics, **2:192–202,** 2:199*t*–201*t*
  gas laws, 2:209–210
  matter, 2:205–207
  resonance, 2:278
  thermal expansion, 2:245–246
  thermodynamics, 2:236–237
  See also Dynamics; Molecules
Molecular mass, 1:112
Molecular motion
  gases, 1:48–49
  matter, 1:37
  See also Brownian motion
Molecular structure, 1:109–111, 1:115–116
  acids and bases, 1:320
  amino acids, 3:11–13, 3:*12*
  proteins, 3:19
  water, 1:347–348
Molecular translational energy, 1:19, 1:22
Molecules, 1:35–36, **1:109–116,** 1:114*t*–115*t*
  Avogadro's number, 1:53
  electromagnetic force, 2:207
  gases, 2:183–184
  molecular dynamics, 2:192–202
  phases of matter, 2:207
  structure, 2:192–193, 4:*315*
  structure of matter, 2:205
  water, 4:*370*
  See also Atoms; Molecular dynamics
Moles (animals), 4:296–297
Moles (measurement), 1:53, 1:81–82
  atomic theory, 2:205–206
  Avogadro's law, 2:184–185
  See also Avogadro's number
Moment arm
  levers, 2:160–162
  screws, 2:166
  torque, 2:87–88
Momentum, **2:37–44**
  See also Angular momentum; Inertia; Linear momentum
Monad, 2:300
Monera, 3:198
Monetary inflation, 1:*4,* 1:6
Monism, 3:167
Monomers, 1:372, 1:375
Monosaccharides, 3:3–4
Monotreme order, 3:218
Montagu, Lady Mary Wortley, 3:256
Montane forests, 3:363
Montgolfier, Jacques-Etienne, 2:105, 2:126, 2:144
Montgolfier, Joseph-Michel, 2:105, 2:126, 2:144
Moon, 4:74–77
  astronomy and measurement, 4:80, 4:82–84
  composition, 4:75–76
  Earth-Moon system, 4:*73*
  exploration, 4:76–77
  glossary, 4:81*t*–83*t*
  lunar cycles, 3:308, 3:313

statistics, 4:75
tidal energy, 4:197–198
Moon walk, 1:*24*
Moraines, 4:380
Morgan, Thomas Hunt, 3:111
Morrison, Herb, 1:257
Mosander, Carl Gustav, 1:207–209
Moseley, Henry
atomic numbers, 1:130
x rays, 1:71
Moss, 3:137
Mothers and babies, 3:73
Moths, 3:138, 3:173
Motion
Aristotelian, 2:15–16
Newton's three laws of motion, 2:18–20
Zeno's paradoxes, 2:14
See also Laws of motion; Linear motion; Projectile motion; Rotational motion
Motion pictures and geoscience, 4:17–18
Motors, 2:27
Mount Etna (Italy), 4:*148*
Mount Everest (Nepal), 2:*142*
Mount Katmai (AK), 4:30
Mount Kilimanjaro (Tanzania), 4:*254*
Mount Machhapuchhare (Himalayas), 4:*246*
Mount McKinley (AK), 4:*275*
Mount Pelée (Martinique) eruption (1815), 4:260
Mount Pinatubo (Philippines) eruption (1991), 4:260, 4:409–410
Mount Saint Helens (WA), 4:30, 4:260
Mount Santo Tomas (Philippines), 4:407–408
Mount Tambora (Indonesia), 4:30
Mountain climbing, 1:*298*
Mountain ranges, 4:256–257
Mountain warfare, 4:263
Mountains, **4:253–263,** 4:261*t*–262*t*
animal migration, 3:336
microclimates, 4:407–408
Transantarctic Mountains (Antarctica), 4:379
See also Volcanoes; *specific mountains and ranges*
Moynihan, Daniel Patrick, 2:338
Mud cracks, 4:*287*
Mudflows. *See* Flow (geology)
Mules, 3:215, 3:*216*
Müller, Johann, 4:65
Municipal waste treatment, 1:360
Murrah Federal Building bombing (1995), 4:*333*
Muscovite, 4:139
Mushrooms, 3:384–385, 3:*385*
Music, 2:274, 2:276, 4:17
Musical instruments, 2:314
Muskets, 2:80
Mussels, 3:71, 3:211
Mutagens, 3:132
Mutation, **3:126–132,** 3:131*t*
DNA, 3:101
early genetics research, 3:111
importance in evolution, 3:164–165
Mutualism (symbiosis), 3:273, 3:383–386, 3:388
Mycobacterium leprae, 3:248
Mycorrhizae, 3:384–386
Mythology and geoscience, 4:5–8

N

Nagasaki bombardment (1945), 1:72, 3:*104*
Naming conventions
amino acids, 3:12–13
binomial nomenclature, 3:206
compounds, 1:276–277
elements, 1:133
geologic time periods, 3:179
germs, 3:283–284
vitamins, 3:88
worms, 3:274
Nanocomputers, 3:120
Nanotechnology, 2:56
Narcolepsy, 3:309
National Geographic Society, 1:256
National Institute of Standards and Technology (NIST), 1:7, 2:8
National Institutes of Health (NIH), 3:103, 3:120
National parks, 3:363
National Weather Service, 4:402–403
Native Americans, 3:127, 3:130–131, 3:186, 3:*207,* 3:396, 4:344–345
Native elements, 4:133–134
Natural convection, 2:228, 4:186
Natural disasters
cyclones, 4:400–402
earthquakes, 4:233–237
mass wasting, 4:277
tornadoes, 4:399–400
volcanoes, 4:257–260
Natural magnets, 2:331–332
See also Magnets
"Natural motion," 1:67–68
Natural polymers, 1:*373*
Natural selection, 3:163–165, 3:204
animal migration, 3:335
behavior, 3:328, 3:393–394
choosing the ideal mate, 3:147–149
See also Evolution
Navigation
animal behavior, **3:335–341,** 3:340*t*
magnetic compass, 2:334
Nazis, 3:*20,* 3:*121,* 3:121–122
Nd YLF lasers, 2:*362*
Neanderthal man, 3:*177*
Necator americanus, 3:278

Negative feedback. *See* Feedback
Nematoda (phylum), 3:349
Neon, 1:*239,* 1:241–242
Neon Canyon (UT), 4:*106*
Neoprene, 1:378
Neptunist stratigraphy, 4:39, 4:88
Nernst, Hermann Walter, 2:223
Nerve cells, 3:*296,* 3:296–297, 3:299, 3:303
Nervous system, 3:295–297, 3:*296*
  See also Brain
Nesosilicates (minerals), 4:135
Net magnetic dipoles, 2:331
Neutralization, 1:322–323
Neutrons, 2:206
  atomic mass, 1:131
  atomic structure, 1:35, 1:66, 1:92
  Chadwick, James, 1:71
  electric charge of atoms, 1:93
New Guinea, 3:396, 3:398
New Madrid (MO) earthquakes, 4:235
New World. *See* Explorers and exploration
New York City (NY), 3:*247,* 3:378, 4:410, 4:*410*
Newcomen, Thomas, 2:231
Newt suit, 2:*145*
Newton, Isaac, 4:*210*
  apples, falling, 2:72
  corpuscular theory of light, 2:290, 2:296, 2:342–343, 2:355–356
  frame of reference, 2:9–10
  gravity, 2:71–77, 4:170
  laws of motion, 2:18–20, 2:59–67
  machines, 2:158
  molecular dynamics, 2:194
  optics, 2:354–355
  Principia, 2:18–20, 2:62
  thermal expansion, 2:245
Newton (unit of measure), 2:73, 2:141, 2:219, 2:229
Newtonian physics
  frame of reference, 2:9–10
  laws of motion, 2:18–20, 2:59–67
  See also Aristotelian Physics; Classical physics; Physics
Newton's three laws of motion. *See* Laws of motion
Niacin, 3:15, 3:95
Niche (ecology), 3:392, 4:352
Nickel, 1:*184,* 1:191
Nicola River Canyon (British Columbia), 4:*265*
Night, 3:311–312
Nile perch, 3:210
Nimbostratus clouds, 4:391–392
Niobium, 1:192
Nissan Hypermini, 1:*163*
NIST (National Institute of Standards and Technology), 1:7, 2:8
Nitrate, 4:335
Nitric oxide, 4:335–336
Nitrification, 4:338
Nitrite, 4:335
Nitrogen, 1:216–218, 2:123–124
  abundance, 4:332–333
  applications, 4:333–334
  biogeochemistry, 4:316
  compounds, 4:334–336
  depletion by leaching soil, 3:352–353
  liquid nitrogen, 4:*332*
  nitrogen cycle, **4:331–338**
  percentage of biosphere, 3:346, 3:348
  properties, 4:333
  used in fertilizers, 3:351
Nitrogen cycle, 3:348, **4:331–338,** 4:336*t*
Nitrogen fixation, 4:334, 4:337–338
Nitrogen gas, 1:59
Nitrogen narcosis, 2:123–124
Noah's Flood (Bible), 4:6
Noble gases, 1:122, 1:214–215, **1:237–242**
Noble metals, 1:122
Nocturnal activities, 3:336–337
Nomenclature. *See* Naming conventions; Taxonomy
Noninfectious diseases, **3:236–243,** 3:243*t*
  See also Diseases, human
Nonmetals, **1:213–221,** 1:220*t*
  anions, 1:103
  compounds, 1:277–278
  families of elements, 1:147
  metalloids, 1:223
Nonsilicate minerals, 4:133–135
Norris, Joe, 2:326–327
Norris, Woody, 2:326–327
North American system of the periodic table of elements, 1:134
  families of elements, 1:140
  transition metals, 1:181–182
  See also Periodic table of elements
Northeast Passage, 3:88
Northern fur seals, 3:*130*
Northern latitudes and midnight sun, 3:310
Northern lights, 4:*79,* 4:79–80
Northern spotted owls, 3:406, 3:408, 4:*354,* 4:354–355
Norway, 3:*309*
Noses, 2:*217*
Novaya Zemlya (Russia), 3:88–89, 3:*89*
Nozzle method of liquefaction, 2:200
Nuclear bombs. *See* Nuclear weapons
Nuclear energy, 2:177, 4:202, 4:206
Nuclear fission, 1:71–72, 1:199–200
Nuclear fusion, 1:72, 1:96–97, 1:255, 4:74, 4:78
Nuclear magnetic resonance, 2:282
Nuclear power, 1:71–72, 1:93, 1:*207*
  Chernobyl nuclear disaster, 1986, 1:98, 1:*103*
  plutonium, 1:201
  uranium, 1:200–201
Nuclear radiation, 3:73

Nuclear weapons, 1:72, 1:98, 1:292–293, 2:177–179, 3:103, 3:*104*
See also Hydrogen bombs
Nuclear weapons testing, 1:177, 4:234
Nucleons, 1:65–66
Nuclides. *See* Isotopes
Numbers, 1:3, 2:6–7
See also Coefficients
Numerical taxonomy, 3:192–193
See also Taxonomy
Nursing mothers, 3:73
Nutrition and nutrients, 3:44–45, **3:77–86,** 3:83*t*–84*t*
amino acids, 3:14–15
carbohydrates, 3:8–10
diseases, 3:230
fats, 3:37
iodine intake, 1:*123*
proteins, 3:22–23
recommended daily allowances (RDA), 1:125–126
vitamins, 3:95–96
See also American diet; German diet
Nylon, 1:*282,* 1:366, 1:378

O

Obduction, 4:257
Obesity, 3:37, 3:39–40, 3:81, 3:127
See also American diet; German diet
Obligate relationships (symbiosis), 3:273–274, 3:383–386
Obligatory taxonomy, 3:193–194, 3:205
See also Taxonomy
Observation, 2:3–4
See also Scientific method
Obstetricians, 3:154
Occupational health
cancer, 3:240
nightshift, 3:309, 3:311
Oceania and marsupials, 3:219
Oceanic crust, 4:*221,* 4:229
Oceanic trenches, 4:224
Oceanography, 4:362
Oceans
biomes, 3:376–377
convection, 4:191
currents, 4:363–364
food webs, 3:77, 3:376–377
Gaia hypothesis, 4:27
ice caps and sea levels, 4:379–380
mass extinctions, 3:182, 3:185
migrations, 3:336
oceanography, 4:362
percentage of Earth's water in, 3:347
phosphorus in, 3:354
water pressure, 2:145
waves, 2:256, 2:258
Ockham's razor, 4:4
Octaves, 2:274, 2:276
Octet rule, 1:103–104, 1:113, 1:214
Odum, Eugene Pleasants, 3:372
Oersted, Hans Christian, 2:340–341, 4:178
Offshore oil drilling, 4:*160*
Ogallala Aquifer (U.S.), 4:*372,* 4:373
Oil films, 2:290, 2:292
Oil industry, 4:158–160
Oil lights, 2:360–361
Oil refineries, 1:*357*
Oils, 1:333–334, 1:*339,* 1:342, 1:347–348
See also Fats and oils
Oklahoma City (OK) bombing (1995), 4:*333*
Old-growth biological communities, 3:369, 3:402, 3:406, 3:408–409
Old-growth forests, 4:354–355
Old people. *See* Elderly
Oldham, Richard, 4:237, 4:240
Oligosaccharides, 3:4
Olivi, Peter John, 2:61
Olympics (Mexico City, 1968), 2:146
Omnivores, 3:361, 4:200
On the Origin of the Species by Means of Natural Selection (Darwin), 3:169
Onnes, Heike Kamerlingh, 2:200
Open systems. *See* Systems
Operant behavior, 3:320
Ophiolites, 4:257
Optical cavities (lasers), 2:361
Optical illusions, 2:359
Optics, 2:20
See also Light
Oranges, 3:93
Orbital filling. *See* Orbital patterns
Orbital patterns, 1:142
actinides, 1:196–197
irregularities, 1:136
principle energy levels, 1:135
representative elements, 1:143–144
transition metals, 1:144, 1:146, 1:184–185
Orbitals, 1:*85,* 1:87–89
electrons, 1:142
Schrödinger, Erwin, 1:74
Orbits (astronomy), 2:75–76, 4:*55,* 4:57
Orchids, 3:138, 3:385
Orders (taxonomy), 3:200, 3:218–226
Ordovician period, 3:182
Ores, 4:161–162
Organ transplants, 3:262–263
Organic and health foods, 3:86
Organic chemistry, 1:245, **1:363–371,** 1:370*t,* 1:373, 4:326
Organic compounds, 1:276, 1:367–368

Organic minerals, 4:134–135
Organic substances
biogeochemical cycles, 3:348
biomes, 3:371
carbon and nutrition, 3:78
distinguished from inorganic, 3:176, 3:391
early life on Earth, 3:178
food webs, 3:361
history, 3:178
Origin of life, 3:178–182
amino acids dating, 3:17
theories of evolution, 3:162
Origin of the universe, 3:177–178
Ornithischia, 3:184
Orogenesis, 4:254–255
See also Tectonism
Orphan metals, 1:156–158, 1:222, 161
Orphan nonmetals, 1:214, 1:219, 1:221
Oscillations, **2:263–269,** 2:268*t*–269*t*
acoustics, 2:311
electromagnetism, 2:343
frequency, 2:272
resonance, 2:278, 2:280–281
See also Harmonic motion; Vibrations; Wave motion
Osmium, 1:191
Osmosis, **1:347–353,** 1:*348,* 1:*350,* 1:352*t*
Osmotic potential, 1:350–351
Osteomalacia, 3:91
Ostrom, John M., 4:128
Outer space. *See* Vacuum
Ovens, microwave, 2:348
Overdamping, 2:266
Overproduction and natural selection, 3:163
Oviparity, 3:151, 3:*152*
Oviviparity, 3:151
Ovulation, 3:143
Owls, 3:406, 3:408
Oxidation, 1:*293*
effect on human body, 3:91
prevention, 4:333
Oxidation numbers, 1:290–291
Oxidation process, 1:218–219
Oxidation-reduction reactions, 1:285, **1:289–296,** 1:*292,* 1:295*t*
Oxidation states, 1:290–291
Oxides (chemicals), 1:218–219
Oxides (minerals), 4:134
Oxpecker, 3:386, 3:*387*
Oxygen, 1:218–219
absorbed in lungs, 3:55
early Earth, 3:178, 3:179
equilibrium, 1:301
mountain climbing, 1:*298*
oxidation-reduction reactions, 1:290
percentage of biosphere, 3:346, 3:348
percentage of human body mass, 3:78
produced in photosynthesis, 3:5, 3:58
quantity on Earth, 1:123
used in fertilizers, 3:351
Oxygen bars, 1:*215,* 1:219
Oxytocin, 3:153
Ozone, 1:233–234, 1:307

P

Packe, Christopher, 4:47
Paired forces, 2:66–67
Paleomagnetism, 4:184, 4:225, 4:228
Paleontology, **3:176–188,** 3:187*t*–188*t,* **4:114–128,** 4:124*t*–126*t*
Paleozoic era, 4:108, 4:116, 4:117
Palladium, 1:191
Palynology, 4:119
Pancreas, human, 3:47
Pangaea, 3:180, 4:220–221
Pangolins, 3:*223,* 3:223–224
Panthalassa, 4:220
Paper airplanes, 2:108
Papin, Denis
hydraulic presses, 2:167
steam engines, 2:231
Parabolas, 2:79
Parachuting. *See* Skydiving
Paradigms, 4:36
Parafoils, 2:108
Parahippus (early horse ancestor), 3:173
Paraho Oil Shale Facility (CO), 4:*159*
Paramagnetism, 2:332
See also Magnetism
Parasites and parasitology, **3:273–282,** 3:280*t*–281*t,* 3:330–331, 3:383–384
Parker, R. L., 4:222–223
Parkes, Alexander, 1:377
Parthenogenesis, 3:137–138
Parthenon (Greece), 3:138
Partial migration, 3:336
Partial pressure (gases), 1:54–55, 2:184–185, 2:187
Particle accelerators, 1:72
Particle-wave hypothesis, 1:87–88
Pascal, Blaise
hydraulic press, 2:160, 2:167
Pascal's principle, 2:96–97, 2:142–143
Pascal (unit of measure), 2:141
Pascal's principle
fluid mechanics, 2:96–97
fluid pressure, 2:142–143
hydraulic presses, 2:98–99, 2:167
Passionflower, 3:389
Pasteur, Louis
lactic acid fermentation, 1:306

pasteurization, 3:288
vaccinations, 3:256, 3:257
Pastuerlla pestis, 3:248
Patented research, 3:121
Pathogens
cause infection, 3:285–286
glossary, 3:284
infectious diseases, 3:245
targeted by immune system, 3:255, 3:262
Patriot missiles, 2:*83*
Pauli exclusion principle, 1:89, 1:142
Pauli, Wolfgang, 1:89
Pauling, Linus, 1:269, 3:*92,* 3:93
Pavlov, Ivan, 3:320
Payen, Anselme, 1:306
Peas, 4:*199*
Peattie, Roderick, 4:255
Pelagic ocean biomes, 3:376
Pellagra, 3:15, 3:95
Pendula
oscillations, 2:267–269
resonance, 2:281–282
See also Pendulum clocks
Pendulum clocks, 2:267, 2:*272,* 2:274
See also Pendula
Pendulums. *See* Pendula
Penicillin, 3:290
Pentadactyl limb, 3:170, 3:*170*
Pepper moths, 3:173
Peptide linkage, 3:13, 3:18
Periodic table of elements, 1:121–122, **1:127–139,** 1:129*t,* 1:137*t*–138*t*
atomic mass units (amu), 1:81
carbon group, 1:244
electron configurations, 1:89–90, 1:364
families of elements, 1:140–147
halogens, 1:229–230
ion formation, 1:102–103
isotopes, 1:71
Mendeleev, Dmitri, 1:69
metals, 1:152–156
noble gases, 1:237
nonmetals, 1:213–215
transition metals, 1:181–185
Periods of the periodic table of elements, 1:127, 1:134, 1:135, 1:142
Periods (wave mechanics)
acoustics, 2:311
Doppler effect, 2:301
electromagnetism, 2:343
frequency, 2:273–274
interference, 2:286–287
resonance, 2:279
ultrasonics, 2:319
waves, 2:257
Perissodactyls, 3:222
Permeability and hydrologic cycle, 4:373
Permian period, 3:182–183
Perpetual motion machines
friction, 2:55
mechanical advantage, 2:158–159
thermodynamics, 2:216, 2:223
See also Machines
Perrin, Jean Baptiste, 2:196, 2:206
Pest control, 2:323–324
Pesticides, 3:*72,* 3:73, 4:358
Petrochemicals, 1:257, 1:367, 1:368, 4:160
Petroleum
economic geology, 4:158–160
fermentation, 3:28, 3:30
fractional distillation, 1:368
remains of dinosaurs, 3:185
See also Fossil fuels
Petroleum industry, 1:*357,* 1:358
Petroleum jelly, 1:*366*
Petrology, 4:147–148
See also Rocks
Pewter, 1:336
pH levels, 1:314, 1:323
Phanerozoic era, 4:108
geologic time, 4:100–101
paleontology, 4:116
Phase diagrams, 1:40–42, 1:*41*
Phases of matter
analogy to human life, 2:211–212
changes, 2:211
molecules, 2:207
temperature, 2:237
thermal expansion, 2:245–246
triple point, 2:214–215
See also Matter
Phenetics, 3:192–193
Phenotype, 3:110
Phenylalanine hydroxylase, 3:37
Phenylketonuria (PKU), 3:37
Pheromones, 3:303–304
Philippine microclimates, 4:407–408
Philosophiae Naturalis Principia Mathematica (Newton). *See Principia*
Phobos (moon), 4:*174*
Pholidota, 3:*223,* 3:223–224
Phoresy (symbiosis), 3:389
Phosphates (minerals), 4:134, 4:317
Phosphor, 2:369
Phosphorescence, 2:367, 2:369–370
Phosphorus, 1:219
biogeochemistry, 4:317–318
importance in nutrition, 3:91
percentage of biosphere, 3:348
phosphorus cycle, 3:354
plants and fungi, 3:384
Phosphorus cycle, 4:317–318

Photoelectric effect
light, 2:343, 2:357
ultraviolet radiation, 2:341–342
Photogeology, 4:54–56
Photogrammetry, 4:53–54
Photography in geoscience, 4:55–56
Photoionization, 1:105–106
Photons, 2:343–344, 2:345, 2:357
See also Corpuscular theory of light; Light; Light waves
Photosynthesis, 1:250, 4:*199*
carbon cycle, 4:330
creation of oxygen, 3:346
energy, 4:199–200
energy transfer, 3:360–361
micorrhizae, 3:385
production of carbohydrates, 3:3, 3:*4,* 3:4–5
stomata, 4:*388*
Phototropism, 3:321
Phyllosilicates (minerals), 4:135
Phylogeny, 3:191–192, 3:195, 3:197–198, 3:204, 3:216, 3:217
Phylum
chordata, 3:205
nematoda, 3:349
Physical changes to matter, 1:34, 1:281–283, 1:289–290, 1:297–298
Physical fitness. *See* Fitness
Physical geodesy, 4:171–172
Physical geology, 4:39–40
Physical oceanography, 4:362
Physical weathering, 4:264, 4:274
Physicians, 3:153–154, 3:238–239
Physics (Aristotle), 2:14–16, 2:61
Physics *vs.* chemistry, 1:119
Physics, classical. *See* Classical physics
Physics (science), 2:13–16
See also Aristotelian physics; Classical physics; Modern physics; Newtonian physics
Phytoplankton, 3:77, 3:376
Pi (coefficient), 2:7, 2:45
Pianos, 2:*273,* 2:*313*
Piccard, Auguste, 2:124, 2:126–127
Piccard, Bertrand, 2:127
Piccard, Jacques, 2:124–125
Picnic at Hanging Rock (movie), 4:17–18
Pictet, Raoul Pierre, 2:200
Picture frames, 2:136
Piedmont glaciers, 4:378
Piezoelectric devices, 2:322–323
Pigeons, 3:338
Pigmentation, 2:359–360
Pillars of Hercules (Mediterranean Sea), 4:5
Pima (Native American tribe), 3:127
Pineapples, 3:*137*
Pinworms, 3:278
Pipes
Bernoulli's principle, 2:97, 2:112–113
fluid pressure, 2:144
Pistons
gas laws, 2:188–189
hydraulic presses, 2:167–169
pumps, 2:99
Pitch (orientation), 2:106
Pivot points, 2:86–87
Place-value numerical system, 1:3
Placenta, 3:153
Placer deposits, 4:288, 4:290
Plagues, 1:360, 3:230, 3:*231,* 3:246–248
Planck, Max, 1:73, 2:343, 2:357
Planetary gears, 2:163
Planetary science, **4:63–71,** 4:69*t*–4:70*t*
density, 4:210
geoscience, 4:35, 4:42
Planetology. *See* Planetary science
Planets
density, 4:210
origin, 3:178
spherical shape, 4:173–174, 4:*174*
Plants
angiosperms *vs.* gymnosperms, 4:347–349
behavior, 3:321
biomes, 3:372–375
blue-green algae, 4:*293*
carbon dioxide, 4:327–328
erosion control, 4:272
evapotranspiration, 3:346, 3:347, 3:354–355, 3:*355*
evolution, 3:173–174
fermentation, 3:28
food webs, 4:200, 4:342
forensics, 3:108
genetic engineering, 3:119
greenhouse effect, 4:355
hybridization, 3:110
introduced species, 3:210–214
kingdom plantae, 3:198
mass wasting, 4:279–280
osmosis, 1:350–351
photosynthesis, 3:4–5, 3:58, 3:77, 3:87–88, 3:346, 3:360–361
protein content, 3:23
reproduction, 3:136–141, 4:347–349
respiration, 4:329–330
selective breeding, 3:128, 3:387
soil formation, 4:293, 4:294
starches and cellulose, 3:6–8
symbiotic relationships, 3:384–386, 3:389
transpiration, 4:389
vegetative propagation, 3:136
See also Fruits and Vegetables; Trees
Plasma (blood), 1:343–344, 3:47

Plasma (matter), 1:42, 2:14, 2:210
Plasmodium, 3:249, 3:276–277
Plastic deformation, 2:150
    See also Deformation
Plastics, 1:*364,* 1:*365,* 1:366–367, 1:375–380
Plate tectonics, **4:219–229,** 4:226*t*–228*t*
    convection, 4:188
    Earth's interior, 4:210–211
    evolution, and, 3:169, 3:180
    mass wasting, 4:277–278
    mid-ocean ridges, 4:*221*
    mountains, 4:253–255
    seismology, 4:228, 4:231–232, 4:237
    uplift, 4:248
    volcanoes, 4:213–214
Platinum, 1:191
Platinum group metals, 1:191–192
Plato (Greek philosopher), 2:359, 3:197, 4:132–133
Platonic solids, 4:132–133, 4:*133*
Pliohippus (horse ancestor), 3:173
"Plum pudding model" (atomic structure), 1:70, 1:86
Plutonism, 4:39
Plutonium, 1:201
Pneumonia, 3:60, 3:62, 3:287
Pohutu Geyser (New Zealand), 4:*196*
Points
    frame of reference, 2:5–6
    Zeno's paradoxes, 2:14
    See also Cartesian system; Coordinates; Graphs
Polar bears, 3:89, 4:*406*
Polar covalent bonding, 1:269
Polar glaciers, 4:378
Polarity of molecules, 3:19
Poliomyelitis, 3:257–258, 3:*287*
Pollen and pollination, 3:138–141, 3:*364,* 3:364–365, 4:119, 4:347–349
Pollution
    cancer-causing, 3:240–241
    impact on biological communities, 3:403
Polonium, 1:226–227
Polyatomic ions, 1:278
Polyester, 1:378–380
Polymerization, 1:375
Polymers, **1:372–380,** 1:*373,* 1:379*t*
    elasticity, 2:152
    made of amino acids, 3:13, 3:18–19
    oscillations, 2:267
    ultrasonics, 2:326
Polysaccharides, 3:4
Pomponius Mela, 4:407
Ponds, 3:375–376
Popocatepetl (volcano), 4:*257*
Popp, Georg, 4:20–21
Pork, 3:277–278
Porous-plug method of liquefaction, 2:200
Porpoises, 3:221, 3:340–341
Positive feedback. *See* Feedback
Post-traumatic stress disorder, 3:232
Potash, 1:167, 1:170
Potassium, 1:167, 1:170
Potassium-argon dating, 1:*238,* 4:98
Potato chip bags, 2:188
Potential energy, 1:11–12, 4:23–24
    Bernoulli's principle, 2:112
    conservation, 2:28–29
    falling objects, 2:174–175
    formulas, 2:29, 2:174
    frequency, 2:271
    oscillations, 2:265–266
    resonance, 2:279
    roller coasters, 2:50
    thermodynamics, 2:217–218
    See also Energy
Pott, Percivall, 3:240
Poverty and the poor
    forced labor, 3:366
    malnutrition, 3:85, 3:95
    occupational health, 3:240
Power, 2:173–174, 2:260
    See also Energy; Force; Work
Power lines, 2:250
Prairie dogs, 4:*297*
Prandtl, Ludwig, 2:113
Precambrian eon
    geologic time, 4:100–101
    life forms, 4:117
    paleontology, 4:115–116
Precession and ice ages, 4:411
Precipitation, **4:387–394,** 4:393*t*–394*t*
    deserts, 3:375
    hydrologic cycle, 4:372
    rain, 3:358, 3:374
Pregnancy, 2:324, **3:151–157,** 3:156*t*
Preservation (food), 1:351–353
Pressure, 1:50–51, 1:300–301, **2:140–147,** 2:146*t*
    See also Air pressure; Fluid pressure
Pressurized oxygen, 1:*298*
Prevost, Pierre, 2:221
Priestley, Joseph, 4:327
    carbon monoxide, identification of, 1:248
    carbonated water, 1:248
Primary colors, 2:360
    See also Colors
Primary succession (ecology), 4:352
Primates, 3:167–168, 3:205–206, 3:216, 3:220–221
Prime Meridian, 2:*5*
    See also Longitude
Prince William Sound earthquake (1964), 4:235
Principia (Newton)
    gravity, 2:72
    laws of motion, 2:18–20, 2:62
Principle energy levels, 1:88–89, 1:135

actinides, 1:196
orbitals, 1:142
transition metals, 1:184
Prisms
diffraction, 2:296–297
infrared light, 2:349
spectrum, 2:354–355
Probability
amino acids in proteins, 3:18–19
base pairs in genes, 3:100, 3:118
Proboscideans, 3:222
Producers (food webs), 3:68
See also Food webs
Projectile motion, **2:78–85,** 2:84*t*
bullets, 2:*79*
Galilean theories, 2:17
human cannonballs, 2:*70*
See also Motion
Proofs. *See* Scientific method
Propagation. *See* Reproduction; Vegetative propagation
Propane, 1:56
Propane tanks, 2:188
Propellants in aerosol cans, 1:55
Propellers
airplanes, 2:106
Bernoulli's principle, 2:116
boat screws, 2:166–167
Properties of matter, **1:33–47,** 1:44*t*–46*t,* 1:49*t*
Prosimii, 3:220–221
Protactinium, 1:199
Proteins, **3:18–23,** 3:22*t,* 3:44
complete proteins, 3:80
content of vegetables, 3:6
importance in nutrition, 3:10, 3:79–80, 3:81–82
made of amino acids, 3:13
synthesis, 3:100–101
Proterozoic eon, 4:116
Protista, 3:198
Protons, 2:206
acids and bases, 1:312–313
atomic structure, 1:35, 1:64, 1:92, 1:130
identified, 1:70–71
Protozoa, 3:275–277
Proust, Joseph-Louis
compounds, 1:112, 1:276, 1:329–330
constant composition, 1:68
Psychological disorders
Alzheimer's disease, 3:*233,* 3:233–235
eating disorders, 3:38–40
mental retardation, 3:334
seasonal affective disorder, 3:314–315
Ptolemy (Greek scientist)
cosmology, 4:38, 4:64–65
geography, 4:45
Pueblo people and desertification, 4:308–309
Pulleys, 2:163–164
Pulses (wave motion), 2:258–259
Pumps
Archimedes screws, 2:166
fluid mechanics, 2:99
Purbach, Georg, 4:65
Pygmies, 3:*128*
Pyramids
construction, 4:36, 4:147
Egyptian, 2:162, 2:164–165
Mayan, 4:*146*
Pyrometers, 1:17, 2:243–244
Pythagoras, 2:14, 4:8

Q

Quantum mechanics, 2:201–202, 3:165–166
Quantum theory
electromagnetism, 2:343–344
electrons, 1:87
light, 2:357
Planck, Max, 1:73
Quarks in electric charges, 1:65–66
Quartz, 4:*136*
Quasi-states of matter, 1:42

R

Rabbits, 3:226
Rabies, 3:257
Race (humans), 3:207
Racing cars, 2:109–110
Radar, 2:348–349, 4:56–57
Radar ranges, 2:348
Radiation (electromagnetism), 2:229, 4:186
cancer-causing, 3:240–241
cancer treatments, 3:239
effects of exposure, 1:98, 3:103, 3:*104*
fire, 2:360
light, 2:356
luminescence, 2:365
microwave ovens, 2:348
nuclear, 3:73
thermodynamics, 2:221
Radiators, 2:248
Radio broadcasting, 2:276–277, 2:345–346
Radio waves
AM and FM transmissions, 2:260–261
discovery, 2:345
FCC spectrum divisions, 2:346–347
frequency, 2:259–260, 2:276–277
luminescence, 2:366
resonance, 2:282
See also Radio broadcasting

Radioactive decay, 1:95, 1:240
absolute dating, 4:97
particle tracks, 4:*96*
Radioactive waste, 1:98
Radioactivity, 1:70–72, 1:94–95, 1:97–98, 1:*177*
actinides, 1:197
thorium, 1:198
uranium, 1:199–200
Radiocarbon dating. *See* Carbon ratio dating
Radioisotopes, 1:95, 1:197
Radiometric dating. *See* Absolute dating
Radium, 1:178–179
Radon, 1:239–240, 1:241
Raiders of the Lost Ark (movie), 4:17–18
Railroad tracks, 2:*246,* 2:250
Rain, 4:279, 4:392
See also Precipitation
Rain clouds, 4:391–392
Rain forests, 4:346
biodiversity, 3:392–393
climate, 3:362–363, 3:373–374
deforestation, 3:365, 3:*366,* 4:*353*
soil, 3:350, 4:297
Rain shadows, 4:260
Rainbows, 2:358–359, 4:78
Ramsay, Sir William, 1:238–239
Rape cases, 3:108–109
Raphus cucullatus, 3:208–209
Rapture of the deep, 2:123–124
Rare Earth-like elements, 1:194–195
Rare gases. *See* Noble gases
Rats, 3:226, 3:330
Rayleigh, John William Strutt, Lord, 1:238–239, 2:358, 4:232
Rayleigh scattering, 2:358
Rayleigh waves, 4:232
Raytheon Manufacturing Company, 2:348
RDA (recommended daily allowances), 1:125–126
Reactants, 1:283, 1:299
Reactivity
halogens, 1:231
noble gases, 1:237
Reagan, Ronald, 2:178–179
Reasoning ability, 3:168
Reaumur, Antoine Ferchault de, 1:15, 2:240
Rebar, 2:151
Receptors (senses), 3:296–297, 3:298–299
Recessive genes, 3:112–113, 3:115
Recommended daily allowances (RDA), 1:125–126
Recording devices, 2:*332,* 2:*333,* 2:336–337
Recycling, 1:380
Red blood cells, 1:351
malaria, 3:276–277
produced by bone marrow, 3:*263*
Red Sea, 4:224, 4:*225*
Red shift, 2:307, 2:358
Redox reactions. *See* Oxidation-reduction reactions
Reflection
optics, 2:354
waves, 2:258–259, 2:356
Reflections on the Motive Power of Fire (Carnot), 2:221–222, 2:231–232
Reflexes, 3:*321,* 3:322
Refraction
optics, 2:354
waves, 2:356
Refrigerators
first law of thermodynamics, 2:222
reverse heat engines, 2:*229,* 2:232
thermodynamics, 2:219–220
Regiomontanus, 4:65
Regolith, 4:265, 4:274, 4:296
Reich, Ferdinand, 1:157–158
Relative dating
geologic time, 4:95–96
paleontology, 3:172, 4:119
stratigraphic column, 4:107
Relative motion
astronomy, 2:8–9
Doppler effect, 2:302–303
relativity, 2:10
See also Relativity
Relativity
atomic theory vs., 1:72–73
conservation of rest energy, 2:29
frame of reference, 2:10
gravity, 2:77
social implications, 2:10–12
syadvada, 2:3–4
See also Relative motion; Rest energy
Religion and science, 3:166–167, 4:3–11, 4:38
creationism, 3:163
historical geology, 4:87–90
planetary science, 4:63–64
See also Roman Catholic Church
Remote sensing, **4:53–59,** 4:58*t*
Earth's interior, 4:212
geodesy, 4:172
geography, 4:52
weather forecasting, 4:402–404
Renne, Paul R., 4:126
Replication of DNA, 3:100–101
Representative elements
atomic size, 1:*141*
electron configuration, 1:136
valence electrons, 1:143–144
Reproduction, **3:135–141,** 3:139*t*–140*t*
See also Asexual reproduction; Sexual reproduction
Reproductive system (human), 3:142–143
Republic (Plato), 2:359
Repulsion, magnetic, 2:337–338

Reservoir rocks, 4:158
Resins in electric charges, 1:106
Resistance thermometers, 2:242–243
Resonance, **2:278–285,** 2:284*t,* 2:288–289
Respiration, **3:55–63,** 3:*59,* 4:329–330
  glossary, 3:61*t*–62*t*
  See also Cellular respiration
Respiratory system, 3:56–58, 3:*59*
Rest energy
  conservation of energy, 2:177
  conservation of matter, 2:203–205
  conservation of rest energy, 2:29
  formula, 2:29, 2:174, 2:179–180
  thermodynamics, 2:218
Restoring force (oscillations), 2:264–265
Resultants (vector mathematics), 2:17
Retroviruses, 3:287
Reverse heat engines, 2:*229,* 2:232
Reverse osmosis, 1:353
Rheumatoid arthritis, 3:268
Rhinoceroses, 3:386, 3:*387*
Rhodium, 1:191–192
Ribonucleic acid. *See* RNA (ribonucleic acid)
Rice, 3:95
Richter, Hieronymus Theodor, 1:157–158
Richter, John, 4:234
Richter scale, 4:234–235
Rickets, 3:*90,* 3:91
Rifles, 2:31, 2:80
Rift valleys
  divergence, 4:224
  oceanic, 4:223
  Red Sea, 4:*225*
  See also Mid-ocean ridges
Right-hand or left-hand amino acids, 3:13, 3:17
Right-hand rules
  electromagnetism, 2:344
  torque, 2:89–90
Right whales, 3:208
River blindness, 3:279
Rivers, 4:374–375
  Bernoulli's principle, 2:*96,* 2:97, 2:113
  biomes, 3:376
  deltas, 3:351, 4:*56,* 4:268, 4:300
  sedimentation, 4:285
  soil, 3:351, 4:300
RNA (ribonucleic acid), 3:101, 3:287
Roads, 2:48
Rock cycle, 4:152–153, 4:288
Rockets
  conservation of linear momentum, 2:31, 2:33
  projectile motion, 2:82–85
  third law of motion, 2:85
Rocks, **4:143–153,** 4:151*t*–152*t*
  arches, 4:*267*
  cap rocks, 4:*159*
  compression, 4:14, 4:*15*
  dating, 4:39, 4:*99*
  deformation, 4:219–220
  sediment sizes, 4:286
  soil formation, 4:292
  See also Petrology
Rocky Mountain bighorn sheep, 3:*323*
Roden Crater (AZ), 4:16
Rodents, 3:224–226
Rodinia, 4:220
Roemer, Olaus, 1:14, 2:239–240
Roentgenology, 2:350, 2:352–353
Rogallo, Francis, 2:108
Roll (orientation), 2:106
Roller coasters, 2:*47,* 2:49–50
Rolling friction, 2:53–54
Roman Catholic Church, 2:16, 2:18, 2:70–71, 4:38
Roman Coliseum, 4:*15*
Roman Empire, 3:230, 3:246, 4:31
Roman numerals used in measurement, 1:3–4
Ronne Ice Shelf, 4:379
Röntgen, Wilhelm, 1:70, 2:350
Roosts (animal territory), 3:324
Rosenberg, Ethel, 2:177
Rosenberg, Julius, 2:177
Ross Ice Shelf, 4:379
Rotational equilibrium, 2:135
  See also Equilibrium
Rotational motion, 2:17
  See also Motion
Roundworms, 3:278
Rowland, Henry Augustus, 2:298
Royal Gorge (CO), 4:270
Royalty and hemophilia, 3:115–116, 3:241
Rozier, Jean-François Pilatre de, 2:126
Rubber, 2:*151,* 2:152, 2:267
Rubidium, 1:170
Ruby lasers, 2:369
Ruminants, 3:7–8, 3:53
Runnels, 4:375
Runoff, 4:373
Rural techno-ecosystems, 3:379–380
Russia
  lag in industrialization, 2:8
  royalty, 3:241, 3:*242*
Rust, 1:*283,* 1:285, 1:294
Ruthenium, 1:192
Rutherford, Daniel, 4:333
Rutherford, Ernest, 1:70–71, 1:*77,* 1:79–80, 1:93, 1:130, 1:*164*

S

Sabin, Albert, 3:257–258
Sabine Pass (TX), 4:*160*

Sahara Desert
caravans, 4:*307*
desertification, 3:353, 4:306–307
sand dunes, 4:*407*
Sahel region desertification, 4:307
Sailors, 3:93
Saliva, human, 3:45
Salk, Jonas, 3:257–258
Salmon, 3:*337*
Salmonella typhosa, 3:251
Salt caravans, 1:*168*
Salt water, 1:343
distillation, 1:355
human body's reaction to, 1:350
reverse osmosis, 1:353
Salts, 1:*230*
formation, 1:111, 1:230
ionic bonding, 1:104
meat curing, 1:352–353
in soil, 3:350
Samarium, 1:*207,* 1:208–209
San Andreas Fault, 4:224
San Blas Indians, 3:130–131
San Francisco earthquake (1906), 4:235
Sand castles, 4:265–266, 4:274
Sandia National Laboratories, 2:56
Sandstone erosion, 4:*26*
Sanitariums for leprosy, 3:248
Sanitary conditions, 3:287–288, 3:288, 3:290
Santos-Dumont, Alberto, 2:127
Satellites
communications satellites, 4:*55*
first law of motion, 2:59–61
gravity, 2:75–76, 4:176
microwave communications, 2:347–348
remote sensing, 4:57, 4:59
Saturated fats, 3:36, 3:88
Saturated hydrocarbons, 1:367–368
Saturation, 1:340–341
Saturn (planet), 1:*26*
Saturn V rockets, 2:85
Sauerkraut, 3:*26*
Saurischia, 3:184
Savannas, 3:*373,* 3:374–375
Savery, Thomas, 2:231
Scalar measurements
speed, 2:17–18
statics and equilibrium, 2:133
work, 2:170–171
See also Measurements; Vector measurements
Scandentia (animal order), 3:220
Scandium (element), 1:194–195
Schistosoma, 3:277
Schools and evolution, 3:169
Schou, Mogens, 1:165
Schrödinger, Erwin, 1:73–74
SCID (Severe combined immune deficiency syndrome). *See* Severe combined immune deficiency syndrome
Science and religion. *See* Religion and science
Scientific laws. *See* Scientific method; *specific laws*
Scientific method
application, 4:36–37
evolution, 3:166–167
glossary, 4:10*t*
origins, 4:3–5, 4:9–11, 4:38
theories and proofs, 3:167
Scientific notation in measurement, 1:4–5
Scientific theories. *See* Scientific method
Screws, 2:165–167
friction, 2:55
mechanical advantage, 2:158
Scrotum cancer, 3:240
Scuba diving. *See* Underwater diving
Scurvy, 3:93
SDI. *See* Strategic Defense Initiative
Sea otters, 3:71
Seaborg, Glenn T., 1:*198*
Seaborgium, 1:133
Seafloor spreading, 4:222
Seal rocks, 4:158
Seals, 3:*130*
Seamounts, 4:258
Seashores, 3:377
See also Beaches
Seasonal affective disorder (SAD), 3:314
Seasons, 3:313–315
Seawalls, 4:401
Second law of motion, 2:18–19, 2:65–66
centripetal force, 2:46
friction, 2:52
gravity, 2:72, 2:73–74
mass, 2:20–21
shopping carts, 2:74
weight, 2:20
See also Force
Second law of thermodynamics, 2:216–217, 2:222–223, 4:195
Earth and energy, 4:198
food webs, 3:69, 3:393
heat, 2:232, 2:234
hydrologic cycle, 4:389
wind, 4:398
See also Entropy
Secondary succession (ecology), 4:352
Seconds (time), 1:9–10
Sediment load, 4:285–286
Sedimentary rocks, 4:149–150, 4:294
Sedimentary structures, 4:288
Sediments and sedimentation, **4:283–291,** 4:289*t*–290*t,* 4:380
Seeds and seed-bearing plants, 3:138

Seesaws, 2:86–89
Seismic waves, 4:232–233
  Earth's interior, 4:237, 4:240–241
  seismograph reading, 4:*233*
Seismographs, 4:*233,* 4:234
Seismology, 4:228, **4:230–241,** 4:238*t*–240*t*
  See also Earthquakes; Volcanoes
Seismoscopes, 2:267
Selective breeding, 3:128, 3:169
Selenium, 1:221, 3:71
Self-contained underwater breathing apparatus (SCUBA), 2:124
Semiconductor lasers, 2:361–362
Semipermeable membranes, 1:106, 1:*348*
Senses, 3:295–305
Separating isotopes, 1:97
Septic tanks, 3:352, 4:306
Sequoia National Park, 3:363
Serotonin, 3:307
Serpentine minerals, 3:71
Severe combined immune deficiency syndrome (SCID), 3:115
Sewage treatment, 1:360
Sewage worms, 3:72
Sexual reproduction, 3:135–141, **3:142–150,** 3:148*t*–149*t,* 3:206–207, 3:215–216
Sexual revolution, 3:147–149
Sexuality. *See* Human sexuality
Sexually transmitted diseases, 3:240, 3:245, 3:258, 3:276
"Sgt. Pepper's Lonely Hearts Club Band" (song), 2:323
Shale, 4:*159*
Shansi earthquake (1556), 4:237
Shear, 2:148
Shedding (fur or skin), 3:313, 3:*313*
Sheep, 3:*122,* 3:123, 3:*323*
Shell shock, 3:232
Shield volcanoes, 4:258
Ships
  buoyancy, 2:22, 2:24–25, 2:121–122
  center of gravity, 2:137
  fluid pressure, 2:144
  introduced species, 3:210
Shock absorbers, 2:266–267
Shopping carts, 2:74
Shores, sea, 3:377
  See also Beaches
Shortwave radio broadcasts, 2:346–347
Shower curtains, 2:117
Shrews, 3:219–220, 3:226
Sickle-cell anemia, 3:*14,* 3:15–16
Siesta, 3:308
Signal propagation, 2:346
Significant figures in measurement, 1:5–6
Silicates (minerals), 1:224–225, 4:135–136, 4:145, 4:160–161
Silicon, 1:224–225, 1:363–364
  economic geography, 4:160–161
  molecular compounds, 1:244
  polymers, 1:372
Silicon wafers, 1:*223*
Silicone surgical implants, 4:*161*
Silicones, 1:225, 4:161
Silver, 1:187–188, 1:*293*
Simmelweis, Ignaz P., 3:288
Simple machines. *See* Machines
Simple sugars, 3:3–4
  See also Sugars
Simpson, O. J., 3:105, 3:*105,* 3:108
Simulated emission of light. *See* Stimulated emission of light
Sine. *See* Trigonometry
Single-displacement reaction, 1:285
Sinkholes, 4:247
Siphon hoses, 2:99
Sirenians, 3:221–222
Skating. *See* Ice skating
Skin, 3:130, 3:244–245, 3:248, 3:262
Skinner, B. F., 3:320–321
Skis, 2:140–141
Sky, color of, 2:358, 4:78–79
Skydiving, 2:*39,* 2:43–44
Sledges, 2:162
Sleep, 3:40, 3:307, 3:308, 3:312–313
  See also Hibernation; Sleep disorders
Sleep disorders, 3:309–311, 3:315
  See also Sleep
Sleet, 4:392
Slides (geology), 4:266–267, 4:276
Sliding friction, 2:53
Slump (geology), 4:266–267, 4:276
Small intestine, human, 3:47
Smallpox, 3:230–231, 3:252, 3:256, 3:*257,* 3:*396*
Smell (olfaction), 3:297, 3:299, 3:301–304
Smith, William (geologist), 4:47
  faunal dating, 4:119
  fossil correlation, 4:112
  stratigraphy, 4:105–106
Smith County (KS), 2:137
Smithsonian Institution (Washington, DC), 2:281–282
Snails, 3:*298,* 3:333
Sneath, Peter Henry Andrews, 3:193
Snell, Willebrord, 2:354
Snow, 4:377, 4:392, 4:*392*
Snow, C. P., 2:216–217
Snow, John, 3:288
Snowballs, 2:228
Snowshoes, 2:140–141
Soap, 1:*330,* 1:334, 1:342–343

Social Darwinism, 3:164
Societal views
AIDS, 3:259–261
childbirth, 3:154
evolution, 3:165–169
in vitro fertilization, 3:147–149
Societies and evolution, 3:162–163
Soda cans, 1:54–55, 2:187
Soddy, Frederick, 1:71, 1:*78,* 1:79–80, 1:130
Sodium, 1:166–167
Sodium azide, 1:58–59
Sodium chloride, 1:166–167
Sodium hydrogen carbonate, 1:315–317
Sodium hydroxide, 1:317–318
Sodium substitutes, 1:165
Soft drinks, 1:*248*
Soil, **4:292–300,** 4:298*t*–299*t*
dust bowls, 4:270
erosion, 4:268
formation, 4:301–302
fungi, 3:385–386
layers, 4:302
prairie dogs, 4:*297*
role in biosphere, 3:346–347, 3:348–353
See also Soil conservation
Soil conservation, **4:301–310,** 4:*303,* 4:305–306, 4:308*t*–309*t*
Soil Conservation Service, 4:305
Soil and Water Resources Conservation Act (1977), 4:305
Sokal, Robert Reuven, 3:193
Solar power, 4:*202*
Solar radiation, 4:197
Solar reflectors, 4:*202*
Solar system, 4:*68*
formation, 4:71, 4:72
glossary, 4:81*t*–83*t*
origin, 3:177–178
terrestrial planets, 4:*211*
See also Cosmology; Geocentric universe; Heliocentric universe; Planetary science; Sun; *individual planets*
Solar wind, 4:80
Solenoids, 2:332, 2:334
Solids
acoustics, 2:321
behavior, 2:183
characteristics, 2:148
contrasted with fluids, 2:95–96
freezing, 2:208
liquid crystals, 2:212, 2:214
melting, 2:207–208
properties, 1:49*t*
thermal expansion, 2:249–250
types, 1:37
Solid-state lasers, 2:361–362
Solifluction, 4:266
Solubility, 1:340, 3:35
Solutions, **1:338–346,** 1:344*t*–345*t*
Somatic (body) cells, 3:99, 3:126–127
Somatotropin, 3:307
Sonar
fishing, 2:*321*
ocean floors, 4:223
submarines, 2:*320*
ultrasonics, 2:324–325
Sonic booms
airplanes, 2:106–107
Doppler effect, 2:304–305
See also Compressibility
Sonoluminescence, 2:371
Soot
cause of cancer, 3:240, 3:*240*
industrial melanism, 3:173
Sosa, Sammy, 2:*40*
Sound
compression, 2:304–305
conservation of energy, 2:177
echolocation in animals, 3:339–341
kinetic and potential energy, 2:175–176
luminescence, 2:371
recording, 2:316
speed, 2:311–312, 2:321
See also Acoustics
Sound waves, 2:259
Soup and convection, 4:186
Source rocks, 4:158
South Pole and midnight sun, 3:310
Soviet Union, 2:177–179
Space exploration, 2:129
Space shuttles
fuel, 1:241, 1:*292,* 1:293–294, 2:85
orbit, 2:*60*
Space telescopes, 2:*342*
Space walks, 4:*215*
Spark transmitters, 2:345
Species and speciation, 3:127, **3:204–214,** 3:212*t*–213*t,* **3:215–226,** 3:224*t*–225*t*
competition in communities, 3:393–395
discovering new species, 3:194–195
genetic drift, 3:*112*
geomorphology, 4:262
Homo sapiens, 3:206
Specific gravity, 1:28, 1:30, 2:25–26
Specific heat, 1:17–18, 2:219, 2:230
Spectroscopy
Doppler effect, 2:307
helium, discovery of, 1:238
indium, discovery of, 1:157–158
Spectrum, electromagnetic. *See* Electromagnetic spectrum
Spectrum, light. *See* Light spectrum

Speed
acceleration, 2:17–18
centripetal force, 2:45–46
light, 2:356
sound, 2:259, 2:311–312, 2:321
velocity, 2:17–18, 2:38
Spencer, Percy, 2:348
Sperm cells, 3:100, 3:132, 3:136, 3:142–143
Spiders, 3:330, 3:*332*
Spoilage, foods, 3:27
Spoilers (aerodynamics), 2:110
Spokes (wheels), 2:162
Sponges (animal), 3:*199*
Spongiform encephalopathy, 3:128
Spotted owls, 3:406, 3:408, 4:*354,* 4:354–355
Springs (mechanical)
damping, 2:266
oscillations, 2:263–264
Spruce trees, 3:371
Spur gears, 2:163
Squirrels, 3:*112,* 3:113
Stable equilibrium, 2:263–264
See also Equilibrium
Stagecoaches, 2:163
Stagnation point, 2:105–106
Standards of measurement. *See* Measurements
Staphylococcus, 3:286
Starches, 3:6–7, 3:*7,* 3:25
Starfish, 3:*70,* 3:71
Starvation
children, 3:84–85
dieting technique, 3:81
Static electricity, 1:*102,* 2:340, 4:177
Static friction, 2:53
Statics, **2:133–138,** 2:138*t*
See also Equilibrium
Statue of Liberty (New York, NY), 1:*174*
Steam engines
Carnot's engine, 2:221–222
heat, 2:231–232
Hero of Alexandria, 2:120, 2:163, 2:231
Steamships, 2:121–122
Steel
buoyancy, 2:122
elasticity, 2:*150*
ferromagnetism, 2:334
Steelville (MO), 2:137
Steno, Nicolaus
rock dating, 4:39
stratigraphy, 4:88, 4:105
Stepper motors, 2:337
Steptoe, Patrick, 3:144
Stereochemistry, 1:110–111
Stereoisomers, 1:278
Stereoscopy, 2:298–299, 4:55
Stethoscopes, 2:146–147
Steward, F. C., 3:123
Stickleback fish, 3:217, 3:322, 3:327
Stimulated emission of light, 2:361
Stimuli (living organisms), 3:295, 3:296–297, 3:319, 3:320, 3:321, 3:327–328
Stinger missiles, 2:83
Stingray fossils, 4:*121*
Stoichiometry, 1:286
Stomach, human, 3:46–47, 3:48, 3:*49*
Stomata, 4:*388*
Stone Age, 4:145–147, 4:156–157
Stone carvings, 1:*331*
Stones. *See* Rocks
Strategic Defense Initiative (SDI), 2:178–179
Stratigraphy, **4:105–113,** 4:110*t*–112*t*
fossil record, 3:*171,* 3:171–172
history, 4:88
relative dating, 4:96, 4:*99*
Stratocumulus clouds, 4:391
Stratosphere, 2:127
Stratovolcanoes, 4:258
Stratus clouds, 4:391
Streamlined flow. *See* Turbulent flow
Streams (water), 3:376
Strength, ultimate, 2:151
Streptococcus, 3:286
Stress (mechanics), 2:148–149
Stress (psychology), 3:230, 3:232
Striations, 4:*106*
Strohmeyer, Friedrich, 1:189
Strömer, Martin, 2:240
Strong acids and bases, 1:322
Strong nuclear force, 2:157
Strontium, 1:176–177
Structural isomerism, 1:278
Strutt, John William, Lord Rayleigh. *See* Rayleigh, John William Strutt, Lord
Subarctic forests, 4:346–347
Subatomic particles, 4:*96*
Sublimation, 1:41, 2:198
Submarines
buoyancy, 2:122–123
sonar, 2:*320,* 2:325
Subpolar forests, 4:346–347
Subpolar glaciers, 4:378
Subsidence
convection, 4:188, 4:190–191
geomorphology, 4:247–248
Subsoil, 4:296
Substrate, 3:25
Subsurface life, 4:296–297
Succession (biological communities), 3:370–371, 3:392, **3:400–409,** 3:407*t*–408*t,* 4:352
Sucrose, 1:109, 3:4
Suess, Eduard, 4:220
Sugars

chemical reactions, 3:25
metabolism, 3:34
molecules, 1:109
nutrition in carbohydrates, 3:9–10
in proteins, 3:19
simple sugars, 3:3–4
Suicide, 3:231
Sulfa drugs, 3:290
Sulfides, 4:134
Sulfur, 1:219, 1:221
acid rain, 4:*318,* 4:321–322
biogeochemistry, 4:318, 4:320–322
percentage of biosphere, 3:348
Sulfur cycle, 4:321–322
Sulfuric acid, 1:315
Sumerian invention of wheel, 2:162
Summer, 3:358
Sun
astronomy and measurement, 4:80, 4:82–84
climate change, 4:409–410
composition, 4:77–78
convection, 4:186–187
glossary, 4:81*t*–83*t*
ice ages, 4:384
nuclear fusion, 4:74
origin of the solar system, 3:177–178
phenomena, 4:78–80
solar radiation, 4:197
statistics, 4:75
weather, 4:396
See also Solar system
Sunburns, 2:*217*
Sunlight
after massive asteroid strike, 3:185
impact on sleep, 3:308, 3:*309,* 3:309–310
in photosynthesis, 3:4–5, 3:360–361
phototropism in plants, 3:321
vitamin D deficiency, 3:91
Sunspots, 4:80
Superatoms, 1:42–43
Superconductivity of helium, 1:242
Superconductors in MAGLEV trains, 2:338
Superfund Act (1980), 4:306
Superman (fictional superhero), 2:44
Superposition, 2:287–288
Supersonic flight, 2:106–107
Surface area, 2:140–141
Surface-to-air missiles, 2:83
Surface water, 4:387–388
Surfactants, 1:333–334, 1:342–343
Surgery
brain, 3:234
fighting cancer, 3:239
Surgical silicone implants, 4:*161*
Suriname toad, 3:*152*
Surveying, 4:47
See also Geography
Survival of the fittest. *See* Evolution; Natural selection
Sushi, 3:*302,* 3:303
Suspended load, 4:285–286
Sutherland, Joan, 2:*314*
Sutton, Walter S., 3:111
Svedberg, Theodor, 2:49
Swallows, 3:338
Swamps, 3:*375,* 3:376
Swimmers, 2:122
Swings
oscillations, 2:263–264
resonance, 2:*279,* 2:281
Syadvada, 2:3–4
Syat, 2:3
Symbiosis, **3:383–390,** 3:388*t,* 3:392
dodo bird and dodo tree, 3:209
parasites, 3:273–274
pollination, 3:140
Sympatric species, 3:217
Synthesis of proteins, 3:19, 3:21–22
Synthesis reactions, 1:285
Synthetic polymers, 1:*374,* 1:*375,* 1:377, 1:378–379
Synthetic rubber, 1:377–378
Systema naturae (Linnaeus), 3:197
Système International d'Unités (SI). *See* Metric system
Systems
biology, 3:345–347
closed systems, 3:345–346
Earth, **4:23–31,** 4:29*t*–30*t*
physics, 2:39
Systolic pressure, 2:147

T

T cells, 3:255, 3:263–264
Table sugar, 3:4
Tacoma Narrows Bridge (WA) collapse, 2:*280,* 2:285
Taiga. *See* Boreal forest
Tambora eruption (1815), 4:260
T'ang-shan (China) earthquake (1976), 4:236–237
Tantalum, 1:192
Tapeworms, 3:277–278
Tarzan (fictional character), 3:331–332
Taste buds, 3:298–299, 3:298–300
Taste (gustation), 3:297, 3:298–304
Taxonomy, 3:202*t*–203*t*
biology, **3:191–203,** 3:204–206, 3:215
biomes, 3:372
history, 3:*192,* 3:*196,* 3:196–198
Linnaean system, 4:118–119
taxonomic keys, 3:193, 3:197
worms and anthropods, 3:274–275
See also Naming conventions

Taylor, Frank Bursley, 4:220
Technetium, 1:195
Tectonism
  mountains, 4:253–254
  plate tectonics, 4:219–220
  seismology, 4:230–231
Tectosilicates (minerals), 4:135
Teeth, 3:222
Telemetry, 2:349
Telescopes, space, 2:*342*
Television broadcasting, 2:346–347
Television tubes, 2:369
Tellurium, 1:226
Temperate forests, 3:373, 4:346–347
Temperate rain forests, 3:373–374
Temperature, **2:236–244,** 2:242*t*–243*t*
  foods, impact on taste, 3:300
  heat, 4:185–186, 4:193–194
  See also Thermal energy; Thermodynamics
Temperature and heat, **1:11–22,** 1:*13,* 1:20*t*–21*t*
  Gay-Lussac's law, 1:56
  saturation, 1:341
Temperature scales, 1:14–16
Tennant, Smithson, 1:191
Tension
  elasticity, 2:148
  modulus, 2:148–149
  statics and equilibrium, 2:134, 2:135–136
  waves, 2:258
Terbium, 1:209
Terminal velocity, 2:74–75
Termites, 3:*6*
Terrestrial biomes, 3:370
Terrestrial planets, 4:210
Territory (animal behavior), 3:324–326
Terrorism, biological, 3:231, 3:251–252
Tesla (unit of measure), 2:335
Testosterone, 3:142
Tetravalent bonds of carbon, 1:245, 1:365
Texture and taste, 3:300
Thales of Miletus (Greek philosopher), 1:67, 2:13–14, 4:177
Thallium, 1:158
Theories. *See* Scientific method
Thermal energy, 1:12–13
  conservation of energy, 2:177
  heat, 2:227–228
  kinetic and potential energy, 2:175–176
  magnetism, 2:332
  molecular dynamics, 2:195
  temperature, 2:236–238
  thermal expansion, 2:245
  thermodynamics, 2:218–219
  See also Temperature
Thermal equilibrium, 2:238–239
Thermal expansion, **2:245–252,** 2:251*t*
  ice, 2:*247*
  railroad tracks, 2:*246*
  temperature, 2:238–239
  See also Thermodynamics
Thermistors, 2:243
Thermocouples, 1:17, 2:243
Thermodynamics, 1:13–14, **2:216–225,** 2:224*t*–225*t*
  chemical thermodynamics, 1:286
  classical physics, 2:20
  laws, 3:69
  red shift, 2:358
  See also Dynamics; Heat; Temperature; Thermal expansion
Thermometers, 2:*238*
  development, 1:14, 2:239–240
  infrared light, 2:349
  mercury, 1:189
  modern, 1:16–17
  temperature, 2:241–244
  thermal expansion, 2:250–251
  volume gas thermometers, 2:249
Thermometric mediums, 2:239–244
Thermoscopes, 2:239
Thermostats, 2:251–252
Thiamine (vitamin B1), 3:92, 3:95
Third law of motion, 2:18, 2:66–67
  gravity, 4:171
  levers, 2:160
  projectile motion, 2:85
  torque, 2:86
  waves, 2:258
Third law of thermodynamics, 2:217, 2:223, 2:234–235, 4:195
Third world nations. *See* Developing nations
Thomas Aquinas, St., 4:4
Thompson, Benjamin, Count Rumford, 2:217, 2:230
Thomson, George Paget, 2:297
Thomson, J. J., 1:70, 1:79, 1:86, 1:130
Thomson, William, Lord Kelvin, 2:*237*
  absolute zero, 1:52, 2:184, 2:197
  heat engines, 2:232
  Kelvin scale, 2:241
  plum pudding model, 1:70
Thorium, 1:198–199
Thunderheads. *See* Cumulonimbus clouds
Thunderstorms, 4:*187,* 4:187–188, 4:391–392, 4:398–399
Thymus gland, 3:263
Tickbirds, 3:386, 3:*387*
Ticks, 3:*279,* 3:282
Tidal energy, 4:197–198
Tidal waves, 3:185
Tides
  currents, 4:364
  Moon, 4:84
  tidal energy, 4:197–198

Till (sediment), 4:380
Time
astronomy and measurement, 4:80, 4:82–84
geologic time, 4:92–94, **4:95–103**
as measurement, 1:9–10
relativity, 2:10
Tin, 1:158
Tinbergen, Nikolaas, 3:320, 3:322–323, 3:327
Tires, 2:*53,* 2:55
See also Cars
Titanic (film), 2:125
Titanic (ship), 2:125
Titanium, 1:192
Titration, 1:323
Toads, 3:123, 3:*152*
Tobacco use
cancer, 3:240
sense of taste and smell, 3:301–302
Toit, Alexander du, 4:220
Tolerance model (biological communities), 3:401
Tongue (human), 3:299–301
Tooth decay and fluoride, 1:233
Toothed gears, 2:163
Topsoil, 4:295–296
Torches, 2:360
Tornado Alley (U.S.), 4:400
Tornadoes, 4:399–400
See also Natural disasters
Torque, **2:86–91,** 2:*88,* 2:160–161
See also Force; Levers
Torque converters, 2:90
Torricelli, Evangelista, 1:50–51, 2:141–142, 2:239
Tortoises, 3:*351*
Toxic shock syndrome (TSS), 3:286
Toxins
bioaccumulation, 3:72–73
indicator species, 3:71–72
targeted by immune system, 3:262
Trace elements in human body, 1:123–126, 3:78
Tracheal respiration, 3:57
Train whistles, 2:*302,* 2:303–304
Trains and magnetic levitation, 2:337–339
Trampolines, 2:*264*
Transantarctic Mountains (Antarctica), 4:379
Transducers, 2:322–323, 2:349
Transform motion (plate tectonics), 4:224
Transgenic animals or plants, 3:103
Transition metals, 1:136, 1:154–155, **1:181–195,** 1:*182,* 1:193*t*–194*t*
compounds, 1:277
orbital patterns, 1:144, 1:146
Translational equilibrium, 2:135
See also Equilibrium
Transmission (wave motion), 2:258–259
Transmissions (automotive)
friction, 2:55
torque, 2:90–91
See also Cars
Transpiration, 3:354–355, 3:358, 4:370, 4:371, 4:389–390
See also Evapotranspiration
Transuranium actinides, 1:201–204
Transuranium elements, 1:133, 1:155, 1:201
Transverse waves, 2:257–258
acoustics, 2:311
diffraction, 2:297
electromagnetism, 2:343–344
frequency, 2:272
luminescence, 2:365
resonance, 2:279
See also Waves
Travel
jet lag, 3:310–311
nighttime air travel, 3:312
Treatise on Electricity and Magnetism (Maxwell), 2:341
Tree lines, 4:256
Tree ring dating, 4:119
Trees
conifers, 3:371–372, 3:374
dead trees, 3:408
deciduous trees, 3:373
dodo tree, 3:209
dominate forest ecosystem, 3:362
falling in forests, 2:315
introduced species, 3:210
micorrhizae, 3:385
recovery after logging, 3:406
specialized climate, 3:*362*
tree-dwellers, 3:363
See also Forests
Trevithick, Richard, 2:231
Triangulation in geodesy, 4:49
Triboluminescence, 2:371
Tributary glaciers, 4:380
Triceratops, 3:*183,* 3:184
Trichinosis, 3:278
Trichomonas vaginalis, 3:276
Trieste (bathyscaphe), 2:124–125
Trigonometry
statics and equilibrium, 2:134
tension calculations, 2:136
work, 2:170–171
Trimble, Stanley, 4:286
Trinity Broadcasting Network, 4:216–217
Triple point
graphing, 2:6, 2:*7*
molecular dynamics, 2:198
phases of matter, 2:14, 2:214–215
water, 1:41–42
Tritium, 1:97, 1:*253,* 1:254–255
Trophic levels, 3:68–69, 3:73

Tropical cyclones, 4:400–402, 4:*401*
See also Natural disasters
Tropical forests, 4:*345,* 4:346
Tropics
coral reefs, 3:377, 3:*377*
savannas, 3:*373*
tropical rain forests, 3:350, 3:362–363, 3:365, 3:*366,* 3:374
Tropism, 3:321
Troposphere, 4:405–406
Trucks, 2:110–111
Truffles, 3:385, 3:*385*
Truk Lagoon (Micronesia), 4:*249*
Tryptophan, 3:15
Tuberculosis, 3:60, 3:248–249
Tubificid worms, 3:72
Tubulidentates, 3:222
Tumors, 3:238
Tundra, 3:374, 3:392–393, 3:*394,* 3:394–395
Tungsten, 1:192
Tuning forks, 2:*287,* 2:289–290
Turbidity currents, 4:364
Turbines, 2:101
Turbulent flow
aerodynamics, 2:102–103
Bernoulli's principle, 2:113–115
Turrell, James, 4:16
Turtles, 3:338–339
Twain, Mark, 4:64
Twin studies (genetics), 3:115
Two Cultures and the Scientific Revolution (Snow), 2:216–217
Two New Sciences (Galileo), 2:16–18
Type I-III binary compounds, 1:277
Typhoid fever, 3:251
"Typhoid" Mary Mallon, 3:251
Typhoons, 4:400–402, 4:*401*
See also Natural disasters
Tyrannosaurus rex, 3:184, 4:*115*

U

Udden-Wentworth scale, 4:286
Ulcers, 3:48–49, 3:*49*
Ulmus americana, 3:210
Ultimate strength, 2:151
Ultracentrifuges. *See* Centrifuges
Ultradian rhythms, 3:312–313
Ultrasonic images, 2:324
Ultrasonic speakers, 2:326–327
Ultrasonics, **2:319–327,** 2:327*t,* 3:*155,* 3:155–156
Ultraviolet astronomy, 2:*342,* 2:350
Ultraviolet lamps, 2:368–369
Ultraviolet light, 2:350
astronomy, 2:*342*
electromagnetic spectrum, 2:357–358
fluorescence, 2:368–369
harmful effects, 2:*217*
photoelectric effect, 2:341–342
Unconformities (stratigraphy), 4:112–113
Unconsolidated material
erosion, 4:265–266
mass wasting, 4:274
Undersea diving. *See* Underwater diving
Underwater diving
bends, 1:*50,* 4:334
helium, 1:242
newt suit, 2:*145*
nitrogen, 4:334
partial pressure laws, 1:54
scuba, 2:124, 3:*199*
Unified atomic mass unit. *See* Atomic mass units (amu)
Uniformitarianism, 4:90–92
Uniramia (subphylum), 3:275
United Kingdom
Creutzfeldt-Jakob disease, 3:233
early vaccinations, 3:256–257
royalty, 3:115–116, 3:241
United States
arms race, 2:177–179
center of geography, 2:137
center of population, 2:137
earthquakes, 4:235–236
See also specific government agencies
United States Atomic Energy Commission (AEC), 3:103
United States Bureau of Standards, 2:8
United States Centers for Disease Control and Prevention (CDC), 3:258–259
United States Department of Agriculture (USDA), 3:81, 3:363
United States Department of Energy (DOE), 3:103, 3:120
United States Food and Drug Administration (FDA), 3:79
United States Forest Service, 3:363
United States Naval Observatory, 1:*5*
Units of measure
atmosphere, 2:141–142
calorie, 2:219, 2:229
celsius degrees, 2:240–241
centigrade degrees, 2:240–241
electron volts, 2:345
fahrenheit degrees, 2:240–241
gauss, 2:335
hertz, 2:256–257
horsepower, 2:173
joule, 2:219, 2:229, 2:345
kelvin degrees, 2:184, 2:197
kilocalorie, 2:219, 2:229

kilohertz, 2:256–257
kilowatt, 2:173–174
megahertz, 2:256–257
mole, 2:184–185, 2:193–194, 2:205–206
newton, 2:73, 2:141, 2:219, 2:229
pascal, 2:141
tesla, 2:335
torr, 2:141–142
watt, 2:173
See also Measurements
Universal product code scanners, 2:*296,* 2:299
University of Colorado (CO), 2:49
Unmanned underwater vessels, 2:124–125
Unnamed elements, 1:133
Unsaturated fats. *See* Saturated fats
Unstable equilibrium, 2:263–264
See also Equilibrium
UPC (universal product code) scanners, 2:*296,* 2:299
Uplift and subsidence, 4:248
Upwelling regions (oceans), 3:377
Uranium, 1:199–201, 1:*200*
Uranium series dating, 3:172, 4:98
Uranus (planet), 4:68
Urbain, Georges, 1:209
Urban geology, 4:18
Urban legend of sounds from Hell, 4:216–218
Urey, Harold Clayton, 1:96
Urine and diabetes, 3:242
U.S. dollar, 1:*4*
USDA (U.S. Department of Agriculture), 3:81, 3:363
Ussher, James, 4:7, 4:88
Uterus, 3:152, 3:153
Utopia and Revolution (study), 4:263

V

V-2 rockets, 2:82
Vaccines and vaccination
cancer, 3:239
genetic engineering, 3:103
history, 3:255–256
infectious diseases, 3:249
viruses, 3:287
Vacuum
acoustics, 2:315–316
first law of motion, 2:59–61
gravity, 2:*71*
Valence electrons and configurations, 1:113
actinides, 1:196–197
alkali metals, 1:162
alkaline earth metals, 1:171–173
carbon, 1:243–244, 1:364–365, 4:324
chemical bonding, 1:267–268
halogens, 1:229–230
helium, 1:173
ionic bonding, 1:104
metals, 1:151
minerals, 4:131
periodic table of elements, 1:134, 1:135–136, 1:141–143
principle energy levels, 1:135
representative elements, 1:143–144
transition metals, 1:183–184
Valleys
dry valleys (Antarctica), 4:379
hanging valleys, 4:380
Vampire bats, 3:220
Van Allen belts, 4:80
Vanadium, 1:192
Vaporization curve, 1:40
Variola. *See* Smallpox
V-belt drives, 2:163–164
Vector measurements
collisions, 2:40–41
graphing, 2:133–134
impulse, 2:39–40
linear momentum, 2:37–44
resultants, 2:17
statics and equilibrium, 2:133–135
work, 2:170–171
See also Scalar measurements
Vectors. *See* Vector measurements
Vegetables. *See* Fruits and vegetables
Vegetarians, 3:23
Vegetative propagation, 3:136, 3:*137*
Velcro, 2:53
Velociraptor, 3:184
Velocity
acceleration, 2:17–18
centripetal force, 2:45–46
second law of motion, 2:65
speed, 2:17–18, 2:38
Venerable Bede, 4:39
Venetian blinds, 2:164
Venturi, Giovanni, 2:113
Venturi tubes, 2:113
Venus (planet), 2:129
Verne, Jules, 4:215–216
Vertical motion. *See* Projectile motion
Vestiges, 3:170
Vesuvius (Italy) eruptions, 4:259
Vibrations
frequency, 2:271–272
in matter, 1:37–38
solids, 2:208
ultrasonics, 2:320–321
wave motion, 2:255
See also Oscillations
Vickers scale, 4:156
Villa Luz caves (Mexico), 4:320
Vinci, Leonardo da, 2:360, 4:*89*

fossils, 4:88, 4:105
geology, 4:39
Viruses
cellular activity, 3:285
human immunodeficiency virus (HIV), 3:259–261
infections, 3:286–287
infectious diseases, 3:250–251
respiratory disorders, 3:60
Viscosity
aerodynamics, 2:102–103
airplanes, 2:106
Bernoulli's principle, 2:113
See also Density
Vitamin A, 3:80, 3:88–90
Vitamin B1 (thiamine), 3:92, 3:95
Vitamin B2, 3:92
Vitamin B6, 3:92
Vitamin B12, 3:92, 3:268–269
Vitamin C, 3:*92,* 3:93
Vitamin D, 3:*90,* 3:90–91
Vitamin E, 3:91
Vitamin K, 3:91–92
Vitamins, 3:45, 3:80–81, **3:87–96,** 3:94*t*
Viviparity, 3:151–152
Voices, 2:*314,* 2:315
Volcanic eruptions, 4:258–260
Volcanoes
climate change, 4:409–410
Crater Lake (OR), 4:*259*
mass extinctions, 4:123, 4:126–127
meteorological effects, 4:30–31
Mount Etna (Italy), 4:*148*
Mount Katmai (AK), 4:30
plate tectonics, 4:213–214, 4:228
Popocatepetl, 4:*257*
See also Mountains; Natural disasters; Seismology
Voltaire (French author), 4:233
Volume, **1:23–30, 2:21–26,** 2:25*t*
Volume gas thermometers, 1:16–17, 2:249
Vomiting, 3:39
Vries, Hugo De, 3:111
VSEPR model (valence shell electron pair repulsion), 1:115–116

W

Wakes, boat, 2:*288,* 2:289
Wallace, Alfred Russel, 3:169
Walsh, Don, 2:124–125
Walton, Ernest, 1:*164,* 1:165
Warm-blooded animals, 3:218
Wars
bombs, 1:71–72, 1:93
chlorine gas, 1:231
magnesium in incendiary devices, 1:175–176
Washing machines, 2:49
Waste management, 1:360, 2:49
Wastes, human, 3:50–54
"Watch analogy" (evolution), 3:161–162
Water, 1:*339,* 1:*340,* 1:342
acids and bases, 1:323, 1:326
atomic mass, 1:78–79
biomes, 3:375–377
buoyancy, 2:122
cause of *giardiasis,* 3:276
characteristics, 1:38
chemical equations, 1:283–284
compared to air, 1:49
content of vegetables, 3:6
Earth, 3:178, 4:369–370
erosion, 4:268
eutrophication, 3:354
filtration, 1:358
fluoridation, 1:233
in healthy diet, 3:50
in human digestion, 3:47, 3:88
hydrogen, 1:255
hydrologic cycle, 3:347–348, 4:361–362, **4:369–375**
life, 4:67
molecular polarity, 3:19
molecules, 1:347–348, 4:*370*
percentage of human body mass, 3:78
phase diagram, 1:*41*
pollution, 3:71–72
purity, 1:*266*
red blood cells, 1:351
sedimentation, 4:285
in soil, 3:350, 3:352–353
solvents, 1:347–349
specific heat capacity, 1:17–18
spicy foods, 3:297
Thales of Miletus, 2:13–14
thermometric medium, 2:241–242
triple point, 1:41–42, 2:6
See also Hydrology; Hydrosphere; Ice
Water balloons, 2:44
Water clocks, 2:100–101, 2:163
Water cycle. *See* Hydrologic cycle
Water filtration plants, 1:*356*
Water pressure. *See* Fluid pressure
Waterwheels, 2:99–100, 2:163
Watson, James D., 2:298, 3:111, 3:117
Watt, James, 2:231
Watt (unit of measure), 2:173
Wave mechanical model (atomic structure), 1:87–88
Wave motion, **2:255–261,** 2:260*t*–261*t*
acoustics, 2:311
Doppler effect, 2:301–302

electromagnetism, 2:343–344
frequency, 2:272–273
interference, 2:286–287
light, 2:356–357
resonance, 2:279
See also Harmonic motion; Oscillations
Wavelength, 2:256
diffraction, 2:294–295
electromagnetic waves, 2:343–345
frequency, 2:313
light, 2:357–358
luminescence, 2:366
radio broadcasting, 2:346
See also Frequency
Waves
electromagnetism, 2:341–342
erosion, 4:*26,* 4:268, 4:*284*
interference, 2:286–287
light, 2:355–356
properties, 2:256–258
seismic waves, 4:232–233, 4:*233,* 4:237, 4:240–241
superposition, 2:287–288
See also Light waves; Longitudinal waves; Mechanical waves; Transverse waves
Weak acids and bases, 1:322
Weak nuclear force, 2:157
Weather, **4:395–404,** 4:403*t*
chaos theory, 4:24–25
mountains, 4:260
El Niño, 4:28, 4:30
volcanoes, 4:30–31
water in the atmosphere, 3:347–348, 3:358
See also Climate; Meteorology
Weathering
erosion, 4:264–266
mass wasting, 4:273–274
sedimentation, 4:283–284
Wedges, 2:165
Wegener, Alfred, 4:220–222
Weight
buoyancy, 2:120–121
friction, 2:52–53
gravity, 2:72–74, 4:173
mass, 1:24–25, 1:76, 2:19–20
second law of motion, 2:65
See also Mass
Weight loss. *See* Fitness
Weightlifting, 3:308
Weizmann Institute, 3:120
Werner, Abraham Gottlob, 4:39, 4:88
Western Deeps Gold Mine (South Africa), 4:212
Wetlands, 3:376
Whales
echolocation, 3:*339,* 3:340–341
endangered species, 3:*207,* 3:208
taxonomy, 3:195, 3:204–205, 3:222
Wheat, 3:352
Wheelbarrows, 2:161–163
Wheels, 2:109, 2:162–164
Whirlpools, 4:*363*
Whitcomb, Richard, 2:107
White, Vanna, 2:228
Whittaker, Jim, 2:*142*
WHKY radio station (Hickory, NC), 2:293
Wilkins, Maurice Hugh Frederick, 2:297–298
William of Ockham, 4:4
Williamson, William, 1:306
Willm, Pierre-Henri, 2:124
Wilson, Brian, 2:127
Wilson, Edward O., 3:402
Wilson, John Turzo, 4:222
Wind
convection, 4:188
weather, 4:397–398
Wind erosion, 4:269–270
dust devils, 4:*269*
sedimentation, 4:285
Wind tunnels, 2:98, 2:107
Windmills, 2:163
Wings
airplanes, 2:105–107
birds, 2:103–105, 2:115, 3:192
paper airplanes, 2:108
Winter
animal migration, 3:335–336
impact on biological rhythms, 3:314–315
The Wizard of Oz (movie), 4:304
Wöhler, Friedrich, 1:245, 1:365, 3:178, 4:326
Wollaston, William Hyde, 1:191
Word origin
kwashiorkor, 3:85
metabolism, 3:33
vitamins, 3:95
See also Naming conventions
Work (labor). *See* Laborers; Occupational health
Work (physics), 2:170–174
definition, 2:222, 2:232
gravity, 2:171–173
power, 2:173–174
thermodynamics, 2:217–218
See also Force; Power
World Trade Center (New York, NY), 1:*153*
World War I, 2:127
World War II
airships, 2:127, 2:129
concentration camps, 3:*121*
Nagasaki bombardment (1945), 3:*104*
World-Wide Standardized Seismograph Network, 4:234
Worms
acorn worm, 3:*138*

detritivores, 3:349
parasites, 3:275, 3:277–279
soil formation, 4:296
taxonomy, 3:274–275
Wrenches, 2:86–89, 2:160–161
Wright, Orville, 2:105, 2:116
Wright, Wilbur, 2:105, 2:116
Wuncheria bancrofti, 3:*278,* 3:279
www.Gravity.org, 2:77

X

X-axis. *See* Axes
X-ray diffraction, 2:298
X-rays, 2:350
applications, 2:352–353
beryllium, 1:175
diffraction, 2:298
Moseley, Henry, 1:71
Röntgen, Wilhelm, 1:70
Xenarthrans, 3:219
Xenon, 1:241

Y

Y-axis. *See* Axes
Yachts, 4:27–28
Yaw (orientation), 2:106
Yeast, 3:28, 3:*28*
Yellowstone National Park (U.S.), 3:363
Yersinia pestis, 3:248
Young, Thomas
interference, 2:290, 2:356
wave theory of light, 2:343
Young's modulus, 2:148
Young's modulus of elasticity, 2:148
Ytterbium, 1:209–210
Yttrium, 1:194–195

Z

Z-axis. *See* Axes
Zebra mussels, 3:211
Zeitgebers, 3:309
Zeno of Elea, 2:14
Zeppelin, Ferdinand von, 2:127
Zeppelins, 2:105, 2:127–128
See also Airships
Zhang Heng, 2:267
Zinc, 1:*154,* 1:188–189
Zinc group metals, 1:188–190
Zirconium, 1:192
Zooplankton, 3:336
Zygotes, 3:100, 3:152



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CONTENTS

Introduction v
Advisory Board vii

BIOCHEMISTRY

Carbohydrates 3
Amino Acids 11
Proteins 18
Enzymes 24

METABOLISM

Metabolism 33
Digestion 44
Respiration 55

NUTRITION

Food Webs 67
Nutrients and Nutrition 77
Vitamins 87

GENETICS

Genetics 99
Heredity 110
Genetic Engineering 117
Mutation 126

REPRODUCTION AND BIRTH

Reproduction 135
Sexual Reproduction 142
Pregnancy and Birth 151

EVOLUTION

Evolution 161
Paleontology 176

BIODIVERSITY AND TAXONOMY

Taxonomy 191
Species 204
Speciation 215

DISEASE

Disease 229
Noninfectious Diseases 236
Infectious Diseases 244

IMMUNITY

Immunity and Immunology 255
The Immune System 262

INFECTION

Parasites and Parasitology 273
Infection 283

BRAIN AND BODY

Chemoreception 295
Biological Rhythms 306

LEARNING AND BEHAVIOR

Behavior 319
Instinct and Learning 327
Migration and Navigation 335

THE BIOSPHERE AND ECOSYSTEMS

The Biosphere 345
Ecosystems and Ecology 360
Biomes 370

BIOLOGICAL COMMUNITIES

Symbiosis 383
Biological Communities 391
Succession and Climax 400
General Subject Index 411

INTRODUCTION

Overview of the Series

Welcome to *Science of Everyday Things*. Our aim is to explain how scientific phenomena can be understood by observing common, real-world events. From luminescence to echolocation to buoyancy, the series will illustrate the chief principles that underlay these phenomena and explore their application in everyday life. To encourage cross-disciplinary study, the entries will draw on applications from a wide variety of fields and endeavors.

Science of Everyday Things initially comprises four volumes:

Volume 1: *Real-Life Chemistry*
Volume 2: *Real-Life Physics*
Volume 3: *Real-Life Biology*
Volume 4: *Real-Life Earth Science*

Future supplements to the series will expand coverage of these four areas and explore new areas, such as mathematics.

Arrangement of Real-Life Biology

This volume contains 40 entries, each covering a different scientific phenomenon or principle. The entries are grouped together under common categories, with the categories arranged, in general, from the most basic to the most complex. Readers searching for a specific topic should consult the table of contents or the general subject index.

Within each entry, readers will find the following rubrics:

- **Concept:** Defines the scientific principle or theory around which the entry is focused.
- **How It Works:** Explains the principle or theory in straightforward, step-by-step language.
- **Real-Life Applications:** Describes how the phenomenon can be seen in everyday life.
- **Where to Learn More:** Includes books, articles, and Internet sites that contain further information about the topic.

In addition, each entry includes a "Key Terms" section that defines important concepts discussed in the text. Finally, each volume includes many illustrations and photographs throughout.

In addition, readers will find the comprehensive general subject index valuable in accessing the data.

About the Editor, Author, and Advisory Board

Neil Schlager and Judson Knight would like to thank the members of the advisory board for their assistance with this volume. The advisors were instrumental in defining the list of topics, and reviewed each entry in the volume for scientific accuracy and reading level. The advisors include university-level academics as well as high school teachers; their names and affiliations are listed elsewhere in the volume.

Neil Schlager is the president of Schlager Information Group Inc., an editorial services company. Among his publications are *When Technology Fails* (Gale, 1994); *How Products Are Made* (Gale, 1994); the *St. James Press Gay and Lesbian Almanac* (St. James Press, 1998); *Best Literature By and About Blacks* (Gale, 2000); *Contemporary Novelists*, 7th ed. (St. James Press,

2000); *Science and Its Times* (7 vols., Gale, 2000-2001); and *Science in Dispute* (Gale, 2002). His publications have won numerous awards, including three RUSA awards from the American Library Association, two Reference Books Bulletin/Booklist Editors' Choice awards, two New York Public Library Outstanding Reference awards, and a *CHOICE* award for best academic book.

Judson Knight is a freelance writer, and author of numerous books on subjects ranging from science to history to music. His work on science includes *Science, Technology, and Society, 2000 B.C.-A.D.* 1799 (U•X•L, 2002), as well as extensive contributions to Gale's seven-volume *Science and Its Times* (2000-2001). As a writer on history, Knight has published *Middle Ages Reference Library* (2000), *Ancient Civilizations* (1999), and a volume in U•X•L's *African American Biography* series (1998). Knight's publications in the realm of music include *Parents Aren't Supposed to Like It* (2001), an overview of contemporary performers and genres, as well as *Abbey Road to Zapple Records: A Beatles Encyclopedia* (Taylor, 1999).

COMMENTS AND SUGGESTIONS

Your comments on this series and suggestions for future editions are welcome. Please write: The Editor, *Science of Everyday Things,* Gale Group, 27500 Drake Road, Farmington Hills, MI 48331-3535.

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SCIENCE OF EVERYDAY THINGS

REAL-LIFE BIOLOGY

BIOCHEMISTRY

CARBOHYDRATES

AMINO ACIDS

PROTEINS

ENZYMES

CARBOHYDRATES

CONCEPT

Carbohydrates are nutrients, along with proteins and other types of chemical compounds, but they are much more than that. In addition to sugars, of which there are many more varieties than ordinary sucrose, or table sugar, carbohydrates appear in the form of starches and cellulose. As such, they are the structural materials of which plants are made. Carbohydrates are produced by one of the most complex, vital, and amazing processes in the physical world: photosynthesis. Because they are an integral part of plant life, it is no wonder that carbohydrates are in most fruits and vegetables. And though they are not a dietary requirement in the way that vitamins or essential amino acids are, it is difficult to eat without ingesting some carbohydrates, which are excellent sources of quick-burning energy. Not all carbohydrates are of equal nutritional value, however: in general, the ones created by nature are good for the body, whereas those produced by human intervention—some forms of pasta and most varieties of bread, white rice, crackers, cookies,and so forth—are much less beneficial.

HOW IT WORKS

What Carbohydrates Are

Carbohydrates are naturally occurring compounds that consist of carbon, hydrogen, and oxygen, and are produced by green plants in the process of undergoing photosynthesis. In simple terms, photosynthesis is the biological conversion of light energy (that is, electromagnetic energy) from the Sun to chemical energy in plants. It is an extremely complex process, and a thorough treatment of it involves a great deal of technical terminology. Although we discuss the fundamentals of photosynthesis later in this essay, we do so only in the most cursory fashion.

Photosynthesis involves the conversion of carbon dioxide and water to sugars, which, along with starches and cellulose, are some of the more well known varieties of carbohydrate. Sugars can be defined as any of a number of water-soluble compounds, of varying sweetness. (What we think of as sugar—that is, table sugar—is actually sucrose, discussed later.) Starches are complex carbohydrates without taste or odor, which are granular or powdery in physical form. Cellulose is a polysaccharide, made from units of glucose, that constitutes the principal part of the cell walls of plants and is found naturally in fibrous materials, such as cotton. Commercially, it is a raw material for such manufactured goods as paper, cellophane, and rayon.

MONOSACCHARIDES. The preceding definitions contain several words that also must be defined. Carbohydrates are made up of building blocks called monosaccharides, the simplest type of carbohydrate. Found in grapes and other fruits and also in honey, they can be broken down chemically into their constituent elements, but there is no carbohydrate more chemically simple than a monosaccharide. Hence, they are also known as simple sugars or simple carbohydrates.

Examples of simple sugars include glucose, which is sweet, colorless, and water-soluble and appears widely in nature. Glucose, also known as dextrose, grape sugar, and corn sugar, is the principal form in which carbohydrates are assimilated, or taken in, by animals. Other monosaccha-



Micrograph of plant cell chloroplasts, where photosynthesis, the biological conversion of light from the Sun into chemical energy, takes place. Higher plants have these structures, which contain a chemical known as chlorophyll that absorbs light and speeds up the process of photosynthesis. *(© Science Pictures Limited/Corbis. Reproduced by permission.)*

rides include fructose, or fruit sugar, and galactose, which is less soluble and sweet than glucose and usually appears in combination with other simple sugars rather than by itself. Glucose, fructose, and galactose are isomers, meaning that they have the same chemical formula ($C_6H_{12}O_6$), but different chemical structures and therefore different chemical properties.

Disaccharides. When two monosaccharide molecules chemically bond with each other, the result is one of three general types of complex sugar: a disaccharide, oligosaccharide, or polysaccharide. Disaccharides, or double sugars, are composed of two monosaccharides. By far the most well known example of a disaccharide is sucrose, or table sugar, which is formed from the bonding of a glucose molecule with a molecule of fructose. Sugar beets and cane sugar provide the principal natural sources of sucrose, which the average American is most likely to encounter in refined form as white, brown, or powdered sugar.

Another disaccharide is lactose, or milk sugar, the only type of sugar that is produced from animal (i.e., mammal) rather than vegetable sources. Maltose, a fermentable sugar typically formed from starch by the action of the enzyme amylase, is also a disaccharide. Sucrose, lactose, and maltose are all isomers, with the formula $C_{12}H_{22}O_{11}$.

Oligosaccharides and polysaccharides. The definitions of oligosaccharide and polysaccharide are so close as to be confusing. An oligosaccharide is sometimes defined as a carbohydrate containing a known, small number of monosaccharide units, while a polysaccharide is a carbohydrate composed of two or more monosaccharides. In theory, this means practically the same thing, but in practice, an oligosaccharide contains 3-6 monosaccharide units, whereas a polysaccharide is composed of more than six.

Oligosaccharides are found rarely in nature, though a few plant forms have been discovered. Far more common are polysaccharides ("many sugars"), which account for the vast majority of carbohydrate types found in nature. (See Where to Learn More for the Nomenclature of Carbohydrates Web site, operated by the Department of Chemistry at Queen Mary College, University of London. A glance at the site will suggest something about the many, many varieties of carbohydrates.)

Polysaccharides may be very large, consisting of as many as 10,000 monosaccharide units strung together. Given this vast range of sizes, it should not be surprising that there are hundreds of polysaccharide types, which differ from one another in terms of size, complexity, and chemical makeup. Cellulose itself is a polysaccharide, the most common variety known, composed of numerous glucose units joined to one another. Starch and glycogen are also glucose polysaccharides. The first of these polysaccharides is found primarily in the stems, roots, and seeds of plants. As for glycogen, this is the most common form in which carbohydrates are stored in animal tissues, particularly muscle and liver tissues.

Photosynthesis

Photosynthesis, as we noted earlier, is the biological conversion of light or electromagnetic energy from the Sun into chemical energy. It occurs in green plants, algae, and some types of bacteria

and requires a series of biochemical reactions. Higher plants have structures called chloroplasts, which contain a dark green or blue-black chemical known as chlorophyll. Light absorption by chlorophyll catalyzes, or speeds up, the process of photosynthesis. (A catalyst is a substance that accelerates a chemical reaction without participating in it.)

In photosynthesis, carbon dioxide and water react with each other in the presence of light and chlorophyll to produce a simple carbohydrate and oxygen. This is one of those statements in the realm of science that at first glance sounds a bit dry and boring but which, in fact, encompasses one of life's great mysteries—a concept far more captivating than any number of imaginary, fantastic, or pseudoscientific ideas one could concoct. Photosynthesis is one of the most essential life-sustaining processes, making possible the nutrition of all things and the respiration of animals and other oxygen-breathing organisms.

In photosynthesis, plants take a waste product of human and animal respiration and, through a series of chemical reactions, produce both food and oxygen. The food gives nourishment to the plant, which, unlike an animal, is capable of producing its own nutrition from its own body with the aid only of sunlight and a few chemical compounds. Later, when the plant is eaten by an animal or when it dies and is consumed by bacteria and other decomposers, it will pass on its carbohydrate content to other creatures. (See Food Webs for more about plants as autotrophs and the relationships among primary producers, consumers, and decomposers.)

A carbohydrate is not the only useful product of the photosynthetic reaction. The reaction produces an extremely important waste by-product—waste, that is, from the viewpoint of the plant, which has no need of oxygen. Yet the oxygen it generates in photosynthesis makes life possible for animals and many single-cell life-forms, which depend on oxygen for respiration.

THE PHOTOSYNTHESIS EQUATION. The photosynthesis reaction can be represented thus as a chemical equation:

$$6CO_2 + 6H_2O \xrightarrow{\text{Light}} C_6H_{12}O_6 + 6O_2$$

Note that the arrow indicates that a chemical reaction has taken place with the assistance of light and chlorophyll. In the same way, heat from a Bunsen burner may be required to initiate some other chemical reaction, without actually being part of the reactants to the left of the arrow. In the present equation, neither the added energy nor the catalyst appears on the left side, because they are not actual physical participants consumed in the reaction, as the carbon dioxide and water are. The catalyst does not participate in the reaction, whereas the energy, while it is consumed in the reaction, is not a material or physical participant—that is, it is energy, not matter.

One might also wonder why the equation shows six molecules of carbon dioxide and six of water. Why not one of each, for the sake of simplicity? To produce a balanced chemical equation, in which the same number of atoms appears on either side of the arrow, it is necessary to show six carbon dioxide molecules reacting with six water molecules to produce six oxygen molecules and a single glucose molecule. Thus, both sides contain six atoms of carbon, 12 of hydrogen, and 18 of oxygen.

The equation gives the impression that photosynthesis is a simple, one-step process, but nothing could be further from the truth. In fact, the process occurs one small step at a time. It also involves many, many intricacies and aspects that require the introduction of scores of new terms and ideas. Such a discussion is beyond the scope of the present essay, and therefore the reader is encouraged to consult a reliable textbook for further information on the details of photosynthesis.

REAL-LIFE APPLICATIONS

Fruits and Vegetables

One of the principal ways in which people obtain carbohydrates from their diets is through fruits and vegetables. The distinctions between these two are based not on science but on custom. Traditionally, vegetables are plant tissues (which may be sweet, but usually are not), that are eaten as a substantial part of a meal's main course. By contrast, fruits are almost always sweet and are eaten as desserts or snacks. It so happens, too, that people are much more likely to cook vegetables than they are fruits, though vegetables are nutritionally best when eaten raw.

Fruits and vegetables are heavy in carbohydrate content, in the form of edible sugars and starches but also inedible cellulose, whose role in the diet will be examined later. In a fresh veg-



Cellulose, sometimes called fiber, is an important dietary component that aids in digestion. It is abundant in fruits and vegetables, yet humans lack the enzyme necessary to digest it. With the help of microbes in their gut, termites can digest cellulose. *(© George D.Lepp/Corbis. Reproduced by permission.)*

etable, for instance, water may account for about 70% of the volume, and proteins, fat, vitamins, and minerals may make up a little more than 5%, with nearly 25% taken up either by edible sugars and starches or by inedible cellulose fiber.

The example of the artichoke. Every fruit or vegetable one could conceivably eat—and there are hundreds—contains both edible carbohydrates, which are a good source of energy, and inedible ones, which provide fiber. An excellent example of this edible-inedible mixture is the globe, or French, artichoke—*Cynara scolymus,* a member of the family Asteraceae, which includes the sunflower. The globe artichoke (not to be confused with the Jerusalem artichoke, or *Helianthus tuberosus*) appears in the form of an inflorescence, or a cluster of flowers. This vegetable usually is steamed, and the bracts, or leaves, are dipped in butter or another sauce.

Not nearly all of the bract is edible, however; to consume the starchy "meat" of the artichoke, which has a distinctive, nutty flavor, one must draw the leaves between the teeth. Most of the artichoke's best parts are thus hidden away, and the best part of all—the tender and fully edible "heart"—is enclosed beneath an intimidating shield of slender thistles. Whoever first discovered that an artichoke could be eaten must have been a brave person indeed, and whoever ascertained *how* to eat it was a wise one. Thanks to these adventurous souls, the world's cuisine has an unforgettable delicacy.

The carbohydrate content of vegetables. In terms of edible carbohydrate content, the artichoke has a low percentage. A few vegetables have a smaller percentage of carbohydrates, whereas others have vastly higher percentages, as the list shown here illustrates. In general, it seems that the carbohydrate content of vegetables (and in each of these cases we are talking about *edible* carbohydrates, not cellulose) is in the range of about 5–10%, somewhere around 20%, or a very high 60–80%. There does not seem to be a great deal of variation in these ranges.

Water, Protein, and Carbohydrate Content of Selected Vegetables:

- Artichoke: 85% water, 2.9% protein, 10.6% carbohydrate
- Beets, red: 87.3% water, 1.6% protein, 9.9% carbohydrate
- Celery: 94.1% water, 0.9% protein, 3.9% carbohydrate
- Corn: 13.8% water, 8.9% protein, 72.2% carbohydrate
- Lima bean: 10.3% water, 20.4% protein, 64% carbohydrate
- Potato: 79.8% water, 2.1% protein, 17.1% carbohydrate
- Red pepper: 74.3% water, 3.7% protein, 18.8% carbohydrate
- Summer squash: 94% water, 1.1% protein, 4.2% carbohydrate

Starches

Not all the carbohydrates in these vegetables are the same. Some carbohydrates appear in the form of sugar and others in the form of inedible cellulose, discussed in the next section. In addition, some vegetables are high in starch content. As we noted earlier, starch is white and granular, and, unlike sugars, starches cannot be dissolved in cold water, alcohol, or other liquids that normally act as solvents.

Manufactured in plants' leaves, starch is the product of excess glucose produced during photosynthesis, and it provides the plant with an emergency food supply stored in the chloroplasts. Vegetables high in starch content are products of plants whose starchy portions happen to be the portions we eat. For example, there is the tuber, or underground bulb, of the potato as well as the seeds of corn, wheat, and rice. Thus, all of these vegetables, and foods derived from them, are heavy in the starch form of carbohydrate.

In addition to their role in the human diet, starches from corn, wheat, tapioca, and potatoes are put to numerous commercial uses. Because of its ability to thicken liquids and harden solids, starch is applied in products (e.g., cornstarch) that act as thickening agents, both for foods and nonfood items. Starch also is utilized heavily in various phases of the garment and garment-care industries to impart stiffness to fabrics. In the manufacture of paper, starch is used to increase the paper's strength. It also is employed in the production of cardboard and paper bags.



NINETEENTH-CENTURY ADVERTISEMENT FOR STARCH. IN ADDITION TO THEIR ROLE IN THE HUMAN DIET, STARCHES ARE PUT TO NUMEROUS COMMERCIAL USES, FOR EXAMPLE, AS THICKENING AGENTS FOR FOOD, IN THE PRODUCTION OF CARDBOARD, AND IN VARIOUS PHASES OF THE GARMENT INDUSTRY TO IMPART STIFFNESS TO FABRICS. *(© BettmannCorbis. Reproduced by permission.)*

CELLULOSE

One of the aspects of fruits and vegetables to which we have alluded several times is the high content of inedible material, or cellulose. (Actually, it is edible—just not digestible.) A substance found in the cell walls of plants, cellulose is chemically like starch but even more rigid, and this property makes it an excellent substance for imparting strength to plant bodies. Animals do not have rigid, walled cells, but plants do. The heavy cellulose content in plants' cell walls gives them their erect, rigid form; in other words, without cellulose, plants might be limp and partly formless. Like human bone, plant cell walls are composed of fibrils (small filaments or fibers) that include numerous polysaccharides and proteins. One of these polysaccharides in cell walls is pectin, a substance that, when heated, forms a gel and is used by cooks in making jellies and jams. Some trees have a secondary cell wall over the primary one, containing yet another polysaccharide called *lignin.* Lignin makes the tree even more rigid, penetrable only with sharp axes.

CELLULOSE IN DIGESTION. As we have noted, cellulose is abundant in fruits and vegetables, yet humans lack the enzyme necessary to digest it. Termites, cows, koalas, and horses all digest cellulose, but even these animals and insect do not have an enzyme that digests this material. Instead, they harbor microbes in their guts that can do the digesting for them. (This is an example of symbiotic mutualism, a mutually beneficial relationship between organisms, discussed in Symbiosis.)

Cows are ruminants, or animals that chew their cud—that is, food regurgitated to be chewed again. Ruminants have several stomachs, or several stomach compartments, that break down plant material with the help of enzymes and bacteria. The partially digested material then is regurgitated into the mouth, where it is chewed to break the material down even further. (If you have ever watched cows in a pasture, you have probably observed them calmly chewing their cud.) The digestion of cellulose by bacteria in the stomachs of ruminants is anaerobic, meaning that the process does not require oxygen. One of the by-products of this anaerobic process is methane gas, which is foul smelling, flammable, and toxic. Ruminants give off large amounts of methane daily, which has some environmentalists alarmed, since cow-borne methane may con-

KEY TERMS

carbohydrates: Naturally occurring compounds, consisting of carbon, hydrogen, and oxygen, whose primary function in the body is to supply energy. Included in the carbohydrate group are sugars, starches, cellulose, and various other substances. Most carbohydrates are produced by green plants in the process of undergoing photosynthesis.

catalyst: A substance that speeds up a chemical reaction without participating in it. Catalysts, of which enzymes are a good example, thus are not consumed in the reaction.

cellulose: A polysaccharide, made from units of glucose, that is the principal material in the cell walls of plants. Cellulose also is found in natural fibers, such as cotton, and is used as a raw material in manufacturing such products as paper.

complex carbohydrate: A disaccharide, polysaccharide, or oligosaccharide. Also called a *complex sugar.*

dextrose: Another name for glucose.

disaccharide: A double sugar, composed of two monosaccharides. Examples of disaccharides include the isomers sucrose, maltose, and lactose.

enzyme: A protein material that speeds up chemical reactions in the bodies of plants and animals.

fructose: Fruit sugar, a monosaccharide that is an isomer of glucose.

galactose: A monosaccharide and isomer of glucose. Less soluble and sweet than glucose, galactose usually appears in combination with other simple sugars rather than by itself.

glucose: A monosaccharide that occurs widely in nature and is the form in which animals usually receive carbohydrates. Also known as dextrose, grape sugar, and corn sugar.

glycogen: A white polysaccharide that is the most common form in which carbohydrates are stored in animal tissues, particularly muscle and liver tissues.

gut: A term that refers to all or part of the alimentary canal, through which foods pass from the mouth to the intestines and wastes move from the intestines to the anus. Although the word is considered a bit crude in everyday life, physicians and biological scientists concerned with this part of the anatomy use it regularly.

isomers: Two substances that have the same chemical formula but differ in

tribute to the destruction of the ozone high in Earth's stratosphere.

Alhough cellulose is indigestible by humans, it is an important dietary component in that it aids in digestion. Sometimes called fiber or roughage, cellulose helps give food bulk as it moves through the digestive system and aids the body in pushing out foods and wastes. This is particularly important inasmuch as it helps make possible regular bowel movements, thus ridding the body of wastes and lowering the risk of colon cancer. (See Digestion for more about the digestive and excretory processes.)

Overall Carbohydrate Nutrition

A diet high in cellulose content can be beneficial for the reasons we have noted. Likewise, a healthy diet includes carbohydrate nutrients, but only under certain conditions. First of all, it should be

KEY TERMS CONTINUED

chemical structure and therefore in chemical properties.

LACTOSE: Milk sugar. A disaccharide isomer of sucrose and maltose, lactose is the only major type of sugar that is produced from animal (i.e., mammal) rather than vegetable sources.

MALTOSE: A fermentable sugar generally formed from starch by the action of the enzyme amylase. Maltose is a disaccharide isomer of sucrose and lactose.

MONOSACCHARIDE: The simplest type of carbohydrate. Monosaccharides, which cannot be broken down chemically into simpler carbohydrates, also are known as simple sugars. Examples of monosaccharides include the isomers glucose, fructose, and galactose.

OLIGOSACCHARIDE: A carbohydrate containing a known, small number of monosaccharide units, typically between three and six. Compare with *polysaccharide.*

PHOTOSYNTHESIS: The biological conversion of light energy (that is, electromagnetic energy) from the Sun to chemical energy in plants. In this process, carbon dioxide and water are converted to carbohydrates and oxygen.

POLYSACCHARIDE: A carbohydrate composed of more than six monosaccharides. A polysaccharide sometimes is defined as containing two or more monosaccharides, but this definition does little to distinguish it from an *oligosaccharide.*

SACCHARIDE: A sugar.

SIMPLE SUGAR: A monosaccharide, or simple carbohydrate.

STARCHES: Complex carbohydrates, without taste or odor, which are granular or powdery in physical form.

SUCROSE: Common table sugar ($C_{12}H_{22}O_{11}$), a disaccharide formed from the bonding of a glucose molecule with a molecule of fructose. Sugar beets and cane sugar provide the principal natural sources of sucrose, which the average American is most likely to encounter in refined form as white, brown, or powdered sugar.

SUGARS: One of the three principal types of carbohydrate, along with starches and cellulose. Sugars can be defined as any of various water-soluble carbohydrates of varying sweetness. What we think of as "sugar" (i.e., table sugar) is actually sucrose.

understood that the human body does not have an essential need for carbohydrates in and of themselves—in other words, there are no "essential" carbohydrates, as there are essential amino acids or fatty acids.

On the other hand, it is very important to eat fresh fruits and vegetables, which, as we have seen, are heavy in carbohydrate content. Their importance has little do with their nutritional carbohydrate content, but rather with the vitamins, minerals, proteins, and dietary fiber that they contain. For these healthy carbohydrates, it is best to eat them in as natural a form as possible: for example, eat the whole orange, rather than just squeezing out the juice and throwing away the pulp. Also, raw spinach and other vegetables contain far more vitamins and minerals than the cooked versions.

SUGAR HIGHS AND FAT STORAGE. Carbohydrates can give people a

short burst of energy, and this is why athletes may "bulk up on carbs" right before competition. But if the carbohydrates are not quickly burned off, they eventually will be stored as fat. This is the case even with healthy carbohydrates, but the situation is much worse with junk-food carbohydrates, which offer only empty calories stripped of vitamin and mineral content. One example is a particular brand of candy bar that, over the years, has been promoted in commercials as a means of obtaining a quick burst of energy. In fact, this and all other white-sugar-based candies give only a quick "sugar high," followed almost immediately by a much lower energy "low"—and in the long run by the accumulation of fat.

Fat is the only form in which the body can store carbohydrates for the long haul, meaning that the "fat-free" stickers on many a package of cookies or cakes in the supermarket are as meaningless as the calories themselves are empty. Carbohydrate consumption is one of the main reasons why the average American is so overweight. With an inactive lifestyle, as is typical of most adults in modern life, all those French fries, cookies, dinner rolls, and so on have no place to go but to the fat-storage centers in the abdomen, buttocks, and thighs. Of all carbohydrate-containing foods, the least fattening, of course, are natural nonstarches, such as fruits and vegetables (assuming they are not cooked in fat). Next on the least-fattening list are starchy natural foods, such as potatoes, and most fattening of all are processed starches, whether they come in the form of rice, wheat, or potato products.

WHY YOU CAN EAT MORE CARBOHYDRATES THAN PROTEINS. One of the biggest problems with starches is that the body can consume so many of them compared with proteins and fats. How many times have you eaten a huge plate of mashed potatoes or rice, mountains of fries, or piece after piece of bread? All of us have done it: with carbohydrates, and particularly starches, it seems we can never get enough. But how many times have you eaten a huge plate of nothing but chicken, steak, or eggs? Probably not very often, and if you have tried to eat too much of these protein-heavy foods at one time, you most likely started to get sick.

The reason is that when you eat protein or fat, it triggers the release of a hormone called *cholecystokinin* (CCK) in the small intestine. CCK tells the brain, in effect, that the body is getting fed, and if enough CCK is released, it signals the brain that the body has received enough food. If one continues to consume proteins or fats beyond that point, nausea is likely to follow. Carbohydrates, on the other hand, do not cause a release of CCK; only when they enter the bloodstream do they finally send a signal to the brain that the body is satisfied. By then, most of us have piled on more mashed potatoes, which are destined to take their place in the body as fat stores.

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AMINO ACIDS

CONCEPT

Amino acids are organic compounds made of carbon, hydrogen, oxygen, nitrogen, and (in some cases) sulfur bonded in characteristic formations. Strings of amino acids make up proteins, of which there are countless varieties. Of the 20 amino acids required for manufacturing the proteins the human body needs, the body itself produces only 12, meaning that we have to meet our requirements for the other eight through nutrition. This is just one example of the importance of amino acids in the functioning of life. Another cautionary illustration of amino acids' power is the gamut of diseases (most notably, sickle cell anemia) that impair or claim the lives of those whose amino acids are out of sequence or malfunctioning. Once used in dating objects from the distant past, amino acids have existed on Earth for at least three billion years—long before the appearance of the first true organisms.

HOW IT WORKS

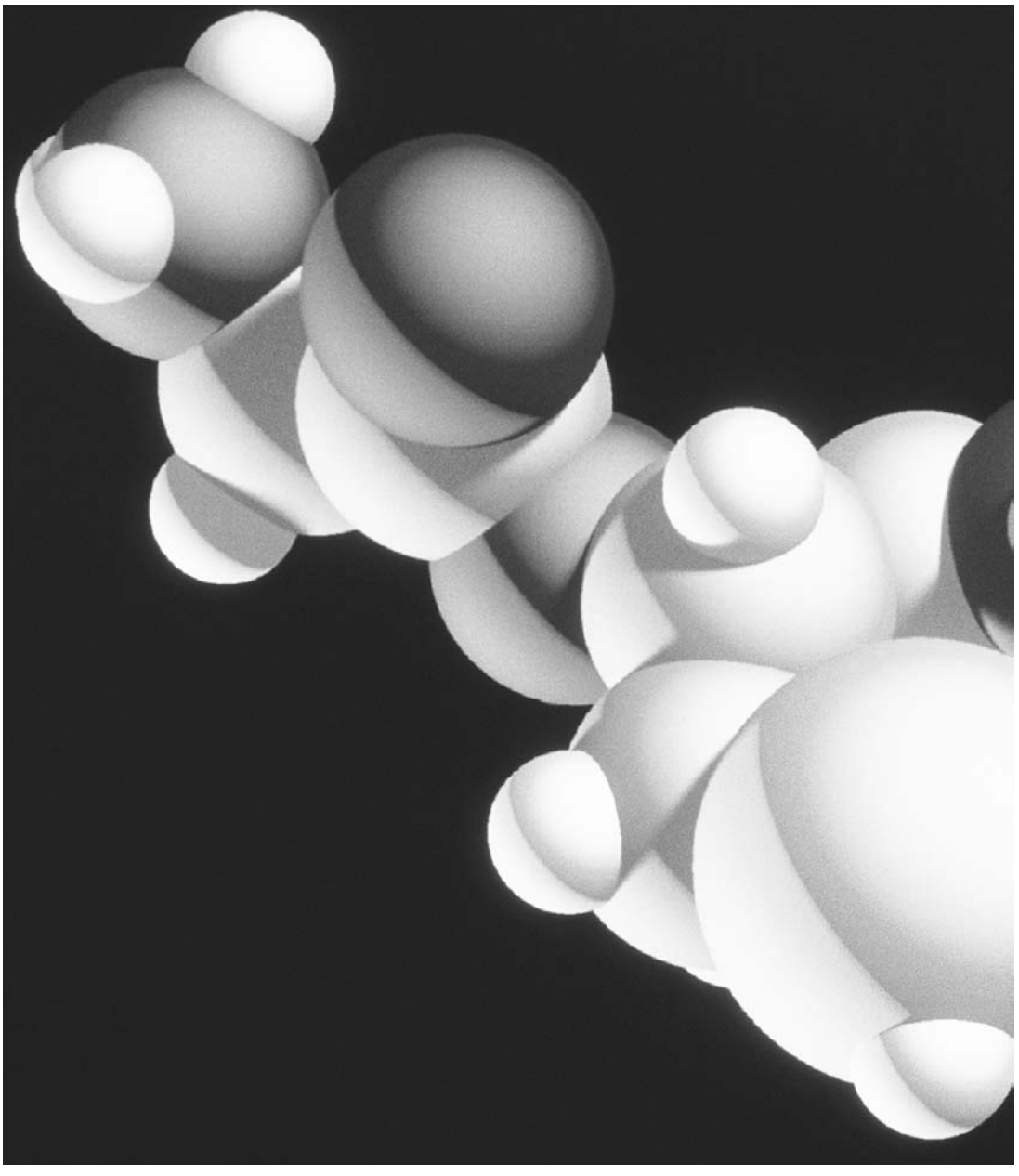
A "Map" of Amino Acids

Amino acids are organic compounds, meaning that they contain carbon and hydrogen bonded to each other. In addition to those two elements, they include nitrogen, oxygen, and, in a few cases, sulfur. The basic structure of an amino-acid molecule consists of a carbon atom bonded to an amino group ($-NH_2$), a carboxyl group (-COOH), a hydrogen atom, and a fourth group that differs from one amino acid to another and often is referred to as the *-R* group or the side chain. The *-R* group, which can vary widely, is responsible for the differences in chemical properties.

This explanation sounds a bit technical and requires a background in chemistry that is beyond the scope of this essay, but let us simplify it somewhat. Imagine that the amino-acid molecule is like the face of a compass, with a carbon atom at the center. Raying out from the center, in the four directions of the compass, are lines representing chemical bonds to other atoms or groups of atoms. These directions are based on models that typically are used to represent amino-acid molecules, though north, south, east, and west, as used in the following illustration, are simply terms to make the molecule easier to visualize.

To the south of the carbon atom (C) is a hydrogen atom (H), which, like all the other atoms or groups, is joined to the carbon center by a chemical bond. To the north of the carbon center is what is known as an amino group ($-NH_2$). The hyphen at the beginning indicates that such a group does not usually stand alone but normally is attached to some other atom or group. To the east is a carboxyl group, represented as -COOH. In the amino group, two hydrogen atoms are bonded to each other and then to nitrogen, whereas the carboxyl group has two separate oxygen atoms strung between a carbon atom and a hydrogen atom. Hence, they are not represented as O_2.

Finally, off to the west is the *R-* group, which can vary widely. It is as though the other portions of the amino acid together formed a standard suffix in the English language, such as *-tion.* To the front of that suffix can be attached all sorts of terms drawn from root words, such as *educate* or



Computer-generated model of a molecule made up of three amino acids—glycine, cysteine and alanine. Amino acids function as monomers, or individual units, that join together to form large, chainlike molecules called polymers; three amino acids bonded together are called tripeptides. *(Photo Researchers. Reproduced by permission.)*

satisfy or *revolt*—hence, *education, satisfaction,* and *revolution.* The variation in the terms attached to the front end is extremely broad, yet the tail end, *-tion,* is a single formation. Likewise the carbon, hydrogen, amino group, and carboxyl group in an amino acid are more or less constant.

A FEW ADDITIONAL POINTS. The name amino acid, in fact, comes from the amino group and the acid group, which are the most chemically reactive parts of the molecule. Each of the common amino acids has, in addition to its chemical name, a more familiar name and a three-letter abbreviation that frequently is used to identify it. In the present context, we are not concerned with these abbreviations. Amino-acid molecules, which contain an amino group and a carboxyl group, do not behave like typical molecules. Instead of melting at temperatures hotter than 392°F (200°C), they simply decom-

pose. They are quite soluble, or capable of being dissolved, in water but are insoluble in nonpolar solvents (oil- and all oil-based products), such as benzene or ether.

RIGHT-HAND AND LEFT-HAND VERSIONS. All of the amino acids in the human body, except glycine, are either right-hand or left-hand versions of the same molecule, meaning that in some amino acids the positions of the carboxyl group and the *R*- group are switched. Interestingly, nearly all of the amino acids occurring in nature are the left-hand versions of the molecules, or the L-forms. (Therefore, the model we have described is actually the left-hand model, though the distinctions between "right" and "left"—which involve the direction in which light is polarized—are too complex to discuss here.)

Right-hand versions (D-forms) are not found in the proteins of higher organisms, but they are present in some lower forms of life, such as in the cell walls of bacteria. They also are found in some antibiotics, among them, streptomycin, actinomycin, bacitracin, and tetracycline. These antibiotics, several of which are well known to the public at large, can kill bacterial cells by interfering with the formation of proteins necessary for maintaining life and for reproducing.

Amino Acids and Proteins

A chemical reaction that is characteristic of amino acids involves the formation of a bond, called a peptide linkage, between the carboxyl group of one amino acid and the amino group of a second amino acid. Very long chains of amino acids can bond together in this way to form proteins, which are the basic building blocks of all living things. The specific properties of each kind of protein are largely dependent on the kind and sequence of the amino acids in it. Other aspects of the chemical behavior of protein molecules are due to interactions between the amino and the carboxyl groups or between the various *R*-groups along the long chains of amino acids in the molecule.

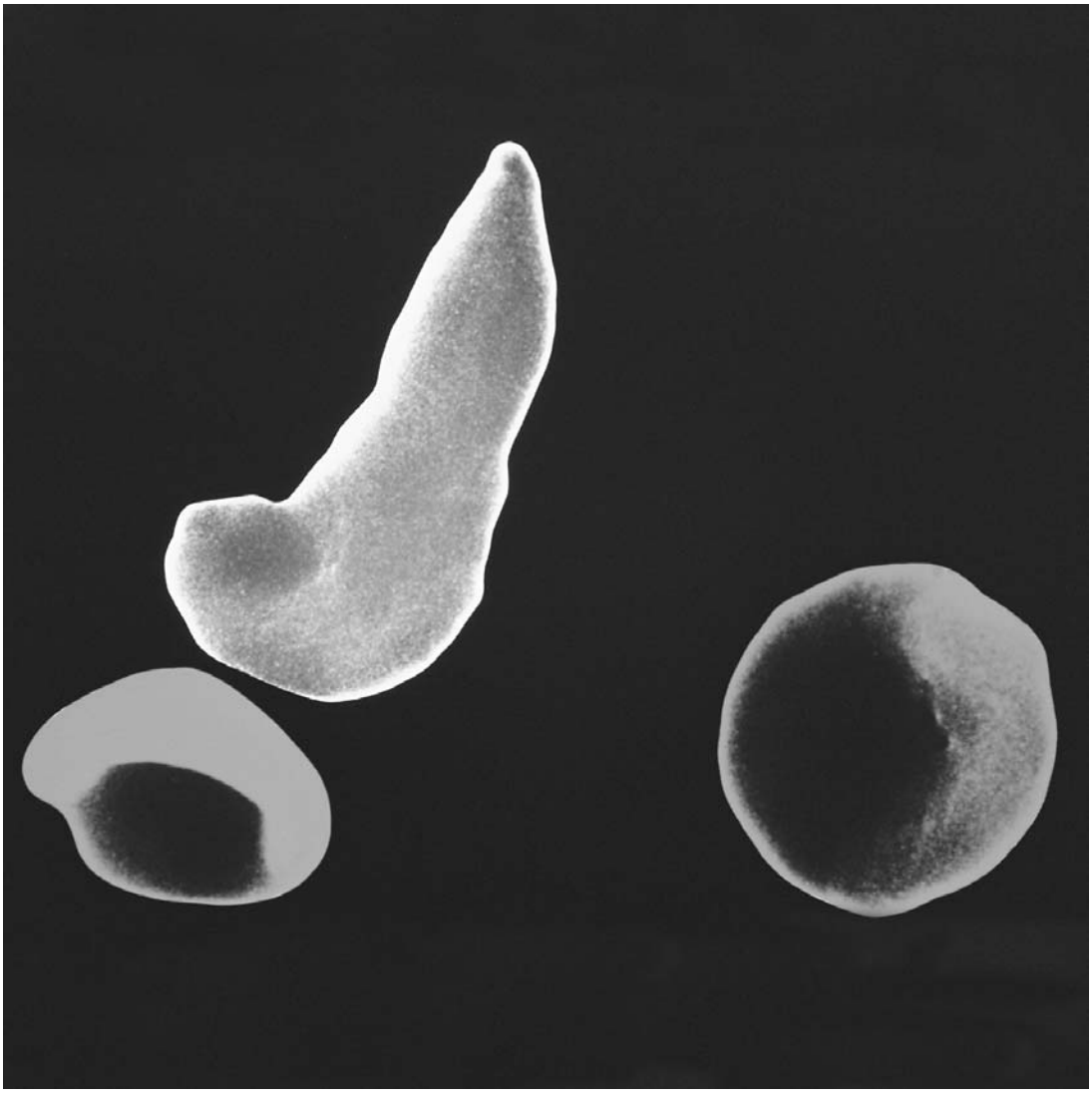
NUMBERS AND COMBINATIONS. Amino acids function as monomers, or individual units, that join together to form large, chainlike molecules called polymers, which may contain as few as two or as many as 3,000 amino-acid units. Groups of only two amino acids are called dipeptides, whereas three amino acids bonded together are called tripeptides. If there are more than 10 in a chain, they are termed polypeptides, and if there are 50 or more, these are known as proteins.

All the millions of different proteins in living things are formed by the bonding of only 20 amino acids to make up long polymer chains. Like the 26 letters of the alphabet that join together to form different words, depending on which letters are used and in which sequence, the 20 amino acids can join together in different combinations and series to form proteins. But whereas words usually have only about 10 or fewer letters, proteins typically are made from as few as 50 to as many as 3,000 amino acids. Because each amino acid can be used many times along the chain and because there are no restrictions on the length of the chain, the number of possible combinations for the formation of proteins is truly enormous. There are about two quadrillion different proteins that can exist if each of the 20 amino acids present in humans is used only once. Just as not all sequences of letters make sense, however, not all sequences of amino acids produce functioning proteins. Some other sequences can function and yet cause undesirable effects, as we shall see.

REAL-LIFE APPLICATIONS

DNA (deoxyribonucleic acid), a molecule in all cells that contains genetic codes for inheritance, creates encoded instructions for the synthesis of amino acids. In 1986, American medical scientist Thaddeus R. Dryja (1940–) used amino-acid sequences to identify and isolate the gene for a type of cancer known as retinoblastoma, a fact that illustrates the importance of amino acids in the body.

Amino acids are also present in hormones, chemicals that are essential to life. Among these hormones is insulin, which regulates sugar levels in the blood and without which a person would die. Another is adrenaline, which controls blood pressure and gives animals a sudden jolt of energy needed in a high-stress situation—running from a predator in the grasslands or (to a use a human example) facing a mugger in an alley or a bully on a playground. Biochemical studies of amino-acid sequences in hormones have made it



Normal red blood cells (bottom) and sickle cell (top). Sickle cell anemia is a fatal disease brought about by a single mistake in amino acid sequencing. When red blood cells release oxygen to the tissues, they fail to re-oxygenate normally and instead twist into the shape that gives sickle cell anemia its name, causing obstruction of the blood vessels. *(Photograph by Dr. Gopal Murti. National Audubon Society Collection/Photo Researchers, Inc. Reproduced by permission.)*

possible for scientists to isolate and produce artificially these and other hormones, including the human growth hormone.

Amino Acids and Nutrition

Just as proteins form when amino acids bond together in long chains, they can be broken down by a reaction called *hydrolysis,* the reverse of the formation of the peptide bond. That is exactly what happens in the process of digestion, when special digestive enzymes in the stomach enable the breaking down of the peptide linkage. (Enzymes are a type of protein—see Enzymes.) The amino acids, separated once again, are released into the small intestine, from whence they pass into the bloodstream and are carried throughout the organism. Each individual cell of the organism then can use these amino acids to assemble the new and different proteins required for its specific functions. Life thus is an ongoing cycle in which proteins are broken into individual amino-acid units, and new proteins are built up from these amino acids.

Essential amino acids. Out of the many thousands of possible amino acids, humans require only 20 different kinds. Two others appear in the bodies of some animal species, and approximately 100 others can be found in

plants. Considering the vast numbers of amino acids and possible combinations that exist in nature, the number of amino acids essential to life is extremely small. Yet of the 20 amino acids required by humans for making protein, only 12 can be produced within the body, whereas the other eight—isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine—must be obtained from the diet. (In addition, adults are capable of synthesizing arginine and histidine, but these amino acids are believed to be essential to growing children, meaning that children cannot produce them on their own.)

A complete protein is one that contains all of the essential amino acids in quantities sufficient for growth and repair of body tissue. Most proteins from animal sources, gelatin being the only exception, contain all the essential amino acids and are therefore considered complete proteins. On the other hand, many plant proteins do not contain all of the essential amino acids. For example, lysine is absent from corn, rice, and wheat, whereas corn also lacks tryptophan and rice lacks threonine. Soybeans are lacking in methionine. Vegans, or vegetarians who consume no animal proteins in their diets (i.e., no eggs, dairy products, or the like) are at risk of malnutrition, because they may fail to assimilate one or more essential amino acid.

Amino Acids, Health, and Disease

Amino acids can be used as treatments for all sorts of medical conditions. For example, tyrosine may be employed in the treatment of Alzheimer's disease, a condition characterized by the onset of dementia, or mental deterioration, as well as for alcohol-withdrawal symptoms. Taurine is administered to control epileptic seizures, treat high blood pressure and diabetes, and support the functioning of the liver. Numerous other amino acids are used in treating a wide array of other diseases. Sometimes the disease itself involves a problem with amino-acid production or functioning. In the essay Vitamins, there is a discussion of pellagra, a disease resulting from a deficiency of the B-group vitamin known as niacin. Pellagra results from a diet heavy in corn, which, as we have noted, lacks lysine and tryptophan. Its symptoms often are described as the "three Ds": diarrhea, dermatitis (or skin inflammation), and dementia. Thanks to a greater understanding of nutrition and health, pellagra has been largely eradicated, but there still exists a condition with almost identical symptoms: Hartnup disease, a genetic disorder named for a British family in the late 1950s who suffered from it.

Hartnup disease is characterized by an inability to transport amino acids from the kidneys to the rest of the body. The symptoms at first seemed to suggest to physicians that the disease, which is present in one of about 26,000 live births, *was* pellagra. Tests showed that sufferers did not have inadequate tryptophan levels, however, as would have been the case with pellagra. On the other hand, some 14 amino acids have been found in excess within the urine of Hartnup disease sufferers, indicating that rather than properly transporting amino acids, their bodies are simply excreting them. This is a potentially very serious condition, but it can be treated with the B vitamin nicotinamide, also used to treat pellagra. Supplementation of tryptophan in the diet also has shown positive results with some patients.

Sickle cell anemia. It is also possible for small mistakes to occur in the amino-acid sequence within the body. While these mistakes sometimes can be tolerated in nature without serious problems, at other times a single misplaced amino acid in the polymer chain can bring about an extremely serious condition of protein malfunctioning. An example of this is sickle cell anemia, a fatal disease ultimately caused by a single mistake in the amino acid sequence. In the bodies of sickle cell anemia sufferers, who are typically natives of sub-Saharan Africa or their descendants in the United States or elsewhere, glutamic acid is replaced by valine at the sixth position from the end of the protein chain in the hemoglobin molecule. (Hemoglobin is an iron-containing pigment in red blood cells that is responsible for transporting oxygen to the tissues and removing carbon dioxide from them.) This small difference makes sickle cell hemoglobin molecules extremely sensitive to oxygen deficiencies. As a result, when the red blood cells release their oxygen to the tissues, as all red blood cells do, they fail to re-oxygenate in a normal fashion and instead twist into the shape

KEY TERMS

AMINO ACIDS: Organic compounds made of carbon, hydrogen, oxygen, nitrogen, and (in some cases) sulfur bonded in characteristic formations. Strings of amino acids make up proteins.

AMINO GROUP: The chemical formation NH_2, which is part of all amino acids.

BIOCHEMISTRY: The area of the biological sciences concerned with the chemical substances and processes in organisms.

CARBOXYL GROUP: The formation -COOH, which is common to all amino acids.

COMPOUND: A substance in which atoms of more than one element are bonded chemically to one another.

DIPEPTIDE: A group of only two amino acids.

DNA: Deoxyribonucleic acid, a molecule in all cells and many viruses containing genetic codes for inheritance.

ENZYME: A protein material that speeds up chemical reactions in the bodies of plants and animals.

ESSENTIAL AMINO ACIDS: Amino acids that cannot be manufactured by the body, and which therefore must be obtained from the diet. Proteins that contain essential amino acids are known as *complete proteins.*

GENE: A unit of information about a particular heritable (capable of being inherited) trait that is passed from parent to offspring, stored in DNA molecules called *chromosomes.*

HORMONE: Molecules produced by living cells, which send signals to spots remote from their point of origin and induce specific effects on the activities of other cells.

MOLECULE: A group of atoms, usually but not always representing more than one element, joined in a structure. Compounds typically are made up of molecules.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to compounds containing carbon and hydrogen.

PEPTIDE LINKAGE: A bond between the carboxyl group of one amino acid and the amino group of a second amino acid.

POLYMERS: Large, chainlike molecules composed of numerous subunits known as *monomers.*

POLYPEPTIDE: A group of between 10 and 50 amino acids.

PROTEINS: Large molecules built from long chains of 50 or more amino acids. Proteins serve the functions of promoting normal growth, repairing damaged tissue, contributing to the body's immune system, and making enzymes.

RNA: Ribonucleic acid, the molecule translated from DNA in the cell nucleus, the control center of the cell, that directs protein synthesis in the cytoplasm, or the space between cells.

SYNTHESIZE: To manufacture chemically, as in the body.

TRIPEPTIDE: A group of three amino acids.

that gives sickle cell anemia its name. This causes obstruction of the blood vessels. Before the development of a treatment with the drug hydroxyurea in the mid-1990s, the average life expectancy of a person with sickle cell anemia was about 45 years.

AMINO ACIDS AND THE DISTANT PAST

The Evolution essay discusses several types of dating, a term referring to scientific efforts directed toward finding the age of a particular item or phenomenon. Methods of dating are either relative (i.e., comparative and usually based on rock strata, or layers) or absolute. Whereas relative dating does not involve actual estimates of age in years, absolute dating does. One of the first types of absolute-dating techniques developed was amino-acid racimization, introduced in the 1960s. As noted earlier, there are "left-hand" L-forms and "right-hand" D-forms of all amino acids. Virtually all living organisms (except some microbes) incorporate only the L-forms, but once the organism dies, the L-amino acids gradually convert to the mirror-image D-amino acids.

Numerous factors influence the rate of conversion, and though amino-acid racimization was popular as a form of dating in the 1970s, there are problems with it. For instance, the process occurs at different rates for different amino acids, and the rates are further affected by such factors as moisture and temperature. Because of the uncertainties with amino-acid racimization, it has been largely replaced by other absolute-dating methods, such as the use of radioactive isotopes.

Certainly, amino acids themselves have offered important keys to understanding the planet's distant past. The discovery, in 1967 and 1968, of sedimentary rocks bearing traces of amino acids as much as three billion years old had an enormous impact on the study of Earth's biological history. Here, for the first time, was concrete evidence of life—at least, in a very simple chemical form—existing billions of years before the first true organism. The discovery of these amino-acid samples greatly influenced scientists' thinking about evolution, particularly the very early stages in which the chemical foundations of life were established.

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PROTEINS

CONCEPT

Most of us recognize the term protein in a nutritional context as referring to a class of foods that includes meats, dairy products, eggs, and other items. Certainly, proteins are an important part of nutrition, and obtaining complete proteins in one's diet is essential to the proper functioning of the body. But the significance of proteins extends far beyond the dining table. Vast molecules built from enormous chains of amino acids, proteins are essential building blocks for living systems—hence their name, drawn from the Greek *proteios,* or "holding first place." Proteins are integral to the formation of DNA, a molecule that contains genetic codes for inheritance, and of hormones. Most of the dry weight of the human body and the bodies of other animals is made of protein, as is a vast range of things with which we come into contact on a daily basis. In addition, a special type of protein called an enzyme has still more applications.

HOW IT WORKS

The Complexities of Biochemistry

Protein is a foundational material in the structure of most living things, and as such it is rather like concrete or steel. Just as concrete is a mixture of other ingredients and steel is an alloy of iron and carbon, proteins, too, are made of something more basic: amino acids. These are organic compounds made of carbon, hydrogen, oxygen, nitrogen, and (in some cases) sulfur bonded in characteristic formations.

Amino acids are discussed in more depth within the essay devoted to that topic, though, as noted in that essay, it is impossible to treat such a subject thoroughly without going into an extraordinarily lengthy and technical discussion. Such is the case with many topics in biochemistry, the area of the biological sciences concerned with the chemical substances and processes in organisms: the deeper within the structure of things one goes, and the smaller the items under investigation, the more complex are the properties and interactions.

The Basics

Amino acids react with each other to form a bond, called a *peptide linkage,* between the carboxyl group of one amino acid (symbolized as -COOH) and the amino group ($-NH_2$) of a second amino acid. In this way they can make large, chainlike molecules called *polymers,* which may contain as few as two or as many as 3,000 amino-acid units. If there are more than 10 units in a chain, the chain is called a *polypeptide,* while a chain with 50 or more amino-acid units is known as a *protein.*

All the millions of different proteins in living things are formed by the bonding of only 20 amino acids into long polymer chains. Because each amino acid can be used many times along the chain, and because there are no restrictions on the length of the chain, the number of possible combinations for the creation of proteins is truly enormous: about two quadrillion, or 2,000,000,000,000,000. Just as not all sequences of letters make sense, however, not all sequences of amino acids produce functioning proteins. In fact, the number of proteins that have significance

in the functioning of nature is closer to about 100,000. This number is considerably smaller than two quadrillion—about 1/2,000,000,000th of that larger number, in fact—but it is still a very large number.

COMPONENTS OTHER THAN AMINO ACIDS. The specific properties of each kind of protein are largely dependent on the kind and sequence of the amino acids in it, yet many proteins include components other than amino acids. For example, some may have sugar molecules (sugars are discussed in the essay on Carbohydrates) chemically attached. Exactly which types of sugars are attached and where on the protein chain attachment occurs vary with the specific protein. Other proteins may have lipid, or fat, molecules chemically bonded to them. Sugar and lipid molecules always are added when synthesis of the protein's amino-acid chain is complete. Many other types of substance, including metals, also may be associated with proteins; for instance, hemoglobin, a pigment in red blood cells that is responsible for transporting oxygen to the tissues and removing carbon dioxide from them, is a protein that contains an iron atom.

STRUCTURES AND SYNTHESIS. Protein structures generally are described at four levels: primary, secondary, tertiary, and quaternary. Primary structure is simply the two-dimensional linear sequence of amino acids in the peptide chain. Secondary and tertiary structures both refer to the three-dimensional shape into which a protein chain folds. The distinction between the two is partly historical: secondary structures are those that were first discerned by scientists of the 1950s, using the techniques and knowledge available then, whereas an awareness of tertiary structure emerged only later. Finally, quaternary structure indicates the way in which many protein chains associate with one another. For example, hemoglobin consists of four protein chains (spirals, actually) of two slightly different types, all attached to an iron atom.

Protein synthesis is the process whereby proteins are produced, or synthesized, in living things according to "directions" given by DNA (deoxyribonucleic acid) and carried out by RNA (ribonucleic acid) and other proteins. As suggested earlier, this is an extraordinarily complex process that we do not attempt to discuss here. Following synthesis, proteins fold up into an essentially compact three-dimensional shape, which is their tertiary structure.



SHEEP SHEARING IN NEW ZEALAND. THE ENTIRE ANIMAL WORLD IS CONSTITUTED LARGELY OF PROTEIN, AS ARE A WHOLE HOST OF ANIMAL PRODUCTS, INCLUDING LEATHER AND WOOL. *(© Adam Woolfitt/Corbis. Reproduced by permission.)*

The steps involved in folding and the shape that finally results are determined by such chemical properties as hydrogen bonds, electrical attraction between positively and negatively charged side chains, and the interaction between polar and nonpolar molecules. Nonpolar molecules are called *hydrophobic,* or "water-fearing," because they do not mix with water but instead mix with oils and other substances in which the electric charges are more or less evenly distributed on the molecule. Polar molecules, on the other hand, are termed *hydrophilic,* or "water-loving," and mix with water and water-based substances in which the opposing electric charges occupy separate sides, or ends, of the molecule. Typically, hydrophobic amino-acid side chains tend to be on the interior of a protein, while hydrophilic ones appear on the exterior.


WANTED

GERMAN SABOTEUR

Photo taken February 19, 1936

WALTER KAPPE, alias Walter Kappel F.P.C. 16 M 28 W 001 M 8 W III

Walter Kappe is known to be connected with sabotage activities being promoted by the Nazi Government. He was born January 12, 1905 at Alfeld, Leina, Germany, and entered the United States on March 9, 1925. He filed application for United States citizenship at Kankakee, Illinois, in June, 1935. He is known to be a member of the German Literary Club, Cincinnati, Ohio, and the Teutonia Club, Chicago, Illinois. Kappe was an agent in the United States for the Ausland Organization and editor "Deutscher Weckruf und Beobachter", official organ of the German-American Bund. Kappe left the United States in 1937 and may return to the United States as an agent for Germany. This individual is described as fol-

U.S. WANTED POSTER FOR A WORLD WAR II NAZI SABOTEUR (JULY 1942). FINGERPRINTS ARE AN EXPRESSION OF OUR DNA, WHICH IS LINKED CLOSELY WITH THE OPERATION OF PROTEINS IN OUR BODIES. *(© Bettmann/Corbis. Reproduced by permission.)*

REAL-LIFE APPLICATIONS

PROTEINS ARE EVERYWHERE

Although it is very difficult to discuss the functions of proteins in simple terms, and it is similarly challenging to explain exactly *how* they function in everyday life, it is not hard at all to name quite a few areas in which these highly important compounds are applied. As we noted earlier, much of our bodies' dry weight—that is, the weight other than water, which accounts for a large percentage of the total—is protein. Our bones, for instance, are about one-fourth protein, and protein makes up a very high percentage of the material in our organs (including the skin), glands, and bodily fluids.

Humans are certainly not the only organisms composed largely of protein: the entire animal world, including the animals we eat and the microbes that enter our bodies (see Digestion

and Parasites and Parasitology) likewise is constituted largely of protein. In addition, a whole host of animal products, including leather and wool, are nearly pure protein. So, too, are other, less widely used animal products, such as hormones for the treatment of certain conditions—for example, insulin, which keeps people with diabetes alive and which usually is harvested from the bodies of mammals.

Proteins allow cells to detect and react to hormones and toxins in their surroundings, and as the chief ingredient in antibodies, which help us resist infection, they play a part in protecting our bodies against foreign invaders. The lack of specific proteins in the brain may be linked to such mysterious, terrifying conditions as Alzheimer and Creutzfeldt-Jakob diseases (discussed in Disease). Found in every cell and tissue and composing the bulk of our bodies' structure, proteins are everywhere, promoting growth and repairing bone, muscles, tissues, blood, and organs.

ENZYMES. One particularly important type of protein is an enzyme, discussed in the essay on that topic. Enzymes make possible a host of bodily processes, in part by serving as catalysts, or substances that speed up a chemical reaction without actually participating in, or being consumed by, that reaction. Enzymes enable complex, life-sustaining reactions in the human body—reactions that would be too slow at ordinary body temperatures—and they manage to do so without forcing the body to undergo harmful increases in temperature. They also are involved in fermentation, a process with applications in areas ranging from baking bread to reducing the toxic content of wastewater. (For much more on these subjects, see Enzymes.)

Inside the body, enzymes and other proteins have roles in digesting foods and turning the nutrients in them—including proteins—into energy. They also move molecules around within our cells to serve an array of needs and allow healthful substances, such as oxygen, to pass through cell membranes while keeping harmful ones out. Proteins in the chemical known as chlorophyll facilitate an exceptionally important natural process, photosynthesis, discussed briefly in Carbohydrates.

PROTEINS, BLOOD, AND CRIME. The four blood types (A, B, AB, and O) are differentiated on the basis of the proteins present in each. This is only one of many key roles that proteins play where blood is concerned. If certain proteins are missing, or if the wrong proteins are present, blood will fail to clot properly, and cuts will refuse to heal. For sufferers of the condition known as hemophilia, caused by a lack of the proteins needed for clotting, a simple cut can be fatal.

Similarly, proteins play a critical role in forensic science, or the application of medical and biological knowledge to criminal investigations. Fingerprints are an expression of our DNA, which is linked closely with the operation of proteins in our bodies. The presence of DNA in bodily fluids, such as blood, semen, sweat, and saliva, makes it possible to determine the identity of the individual who perpetrated a crime or of others who were present at the scene. In addition, a chemical known as luminol assists police in the investigation of possible crime scenes. If blood has ever been shed in a particular area, such as on a carpet, no matter how carefully the perpetrators try to conceal or eradicate the stain, it can be detected. The key is luminol, which reacts to hemoglobin in the blood, making it visible to investigators. This chemical, developed during the 1980s, has been used to put many a killer behind bars.

DESIGNER PROTEINS. These are just a very few of the many applications of proteins, including a very familiar one, discussed in more depth at the conclusion of this essay: nutrition. Given the importance and complexity of proteins, it might be hard to imagine that they can be produced artificially, but, in fact, such production is taking place at the cutting edge of biochemistry today, in the field of "designer proteins."

Many such designs involve making small changes in already existing proteins: for example, by changing three amino acids in an enzyme often used to improve detergents' cleaning power, commercial biochemists have doubled the enzyme's stability in wash water. Medical applications of designer proteins seem especially promising. For instance, we might one day cure cancer by combining portions of one protein that recognizes cancer with part of another protein that attacks it. One of the challenges facing such a development, however, is the problem of designing a protein that attacks *only* cancer cells and not healthy ones.

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PROTEINS: Large molecules built from long chains of 50 or more amino acids. Proteins serve the functions of promoting normal growth, repairing damaged tissue, contributing to the body's immune system, and making enzymes.

RNA: Ribonucleic acid, the molecule translated from DNA in the cell nucleus, the control center of the cell, that directs protein synthesis in the cytoplasm, or the space between cells.

In the long term, scientists hope to design proteins from scratch. This is extremely difficult today and will remain so until researchers better understand the rules that govern tertiary structure. Nevertheless, scientists already have designed a few small proteins whose stability or instability has enhanced our understanding of those rules. Building on these successes, scientists hope that one day they may be able to design proteins to meet a host of medical and industrial needs.

Proteins in the Diet

Proteins are one of the basic nutrients, along with carbohydrates, lipids, vitamins, and miner-

als (see Nutrients and Nutrition). They can be broken down and used as a source of emergency energy if carbohydrates or fats cannot meet immediate needs. The body does not use protein from food directly: after ingestion, enzymes in the digestive system break protein into smaller peptide chains and eventually into separate amino acids. These smaller constituents then go into the bloodstream, from whence they are transported to the cells. The cells incorporate the amino acids and begin building proteins from them.

ANIMAL AND VEGETABLE PROTEINS. The protein content in plants is very small, since plants are made largely of cellulose, a type of carbohydrate (see Carbohydrates for more on this subject); this is one reason why herbivorous animals must eat enormous quantities of plants to meet their dietary requirements. Humans, on the other hand, are omnivores (unless they choose to be vegetarians) and are able to assimilate proteins in abundant quantities by eating the bodies of plant-eating animals, such as cows. In contrast to plants, animal bodies (as previously noted) are composed largely of proteins. When people think of protein in the diet, some of the foods that first come to mind are those derived from animals: either meat or such animal products as milk, cheese, butter, and eggs. A secondary group of foods that might appear on the average person's list of proteins include peas, beans, lentils, nuts, and cereal grains.

There is a reason why the "protein team" has a clearly defined "first string" and "second string." The human body is capable of manufacturing 12 of the 20 amino acids it needs, but it must obtain the other eight—known as *essential amino acids*—from the diet. Most forms of animal protein, except for gelatin (made from animal bones), contain the essential amino acids, but plant proteins do not. Thus, the nonmeat varieties of protein are incomplete, and a vegetarian who does not supplement his or her diet might be in danger of not obtaining all the necessary amino acids.

For a person who eats meat, it would be extremely difficult *not* to get enough protein. According to the U.S. Food and Drug Administration (FDA), protein should account for 10% of total calories in the diet, and since protein contains 4 calories per 0.035 oz. (1 g), that would be about 1.76 oz. (50 g) in a diet consisting of 2,000 calories a day. A pound (0.454 kg) of steak or pork supplies about twice this much, and though very few people sit down to a meal and eat a pound of meat, it is easy to see how a meat eater would consume enough protein in a day.

For a vegetarian, meeting the protein needs may be a bit more tricky, but it can be done. By combining legumes or beans and grains, it is possible to obtain a complete protein: hence, the longstanding popularity, with meat eaters as well as vegetarians, of such combinations as beans and rice or peas and cornbread. Other excellent vegetarian combos include black beans and corn, for a Latin American touch, or the eastern Asian combination of rice and tofu, protein derived from soybeans.

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ENZYMES

CONCEPT

Enzymes are biological catalysts, or chemicals that speed up the rate of reaction between substances without themselves being consumed in the reaction. As such, they are vital to such bodily functions as digestion, and they make possible processes that normally could not occur except at temperatures so high they would threaten the well-being of the body. A type of protein, enzymes sometimes work in tandem with nonproteins called *coenzymes.* Among the processes in which enzymes play a vital role is fermentation, which takes place in the production of alcohol or the baking of bread and also plays a part in numerous other natural phenomena, such as the purification of wastewater.

HOW IT WORKS

Amino Acids, Proteins, and Biochemistry

Amino acids are organic compounds made of carbon, hydrogen, oxygen, nitrogen, and (in some cases) sulfur bonded in characteristic formations. Strings of 50 or more amino acids are known as proteins, large molecules that serve the functions of promoting normal growth, repairing damaged tissue, contributing to the body's immune system, and making enzymes. The latter are a type of protein that functions as a catalyst, a substance that speeds up a chemical reaction without participating in it. Catalysts, of which enzymes in the bodies of plants and animals are a good example, thus are not consumed in the reaction.

Catalysts

In a chemical reaction, substances known as reactants interact with one another to create new substances, called products. Energy is an important component in the chemical reaction, because a certain threshold, termed the activation energy, must be crossed before a reaction can occur. To increase the rate at which a reaction takes place and to hasten the crossing of the activation energy threshold, it is necessary to do one of three things.

The first two options are to increase either the concentration of reactants or the temperature at which the reaction takes place. It is not always feasible or desirable, however, to do either of these things. Many of the processes that take place in the human body, for instance, normally would require high temperatures—temperatures, in fact, that are too high to sustain human life. Imagine what would happen if the only way we had of digesting starch was to heat it to the boiling point inside our stomachs! Fortunately, there is a third option: the introduction of a catalyst, a substance that speeds up a reaction without participating in it either as a reactant or as a product. Catalysts thus are not consumed in the reaction. Enzymes, which facilitate the necessary reactions in our bodies without raising temperatures or increasing the concentrations of substances, are a prime example of a chemical catalyst.

THE DISCOVERY OF CATALYSIS. Long before chemists recognized the existence of catalysts, ordinary people had been using the chemical process known as catalysis for numerous purposes: making soap, fermenting wine to create vinegar, or leavening bread, for

instance. Early in the nineteenth century, chemists began to take note of this phenomenon. In 1812 the Russian chemist Gottlieb Kirchhoff (1764–1833) was studying the conversion of starches to sugar in the presence of strong acids when he noticed something interesting.

When a suspension of starch (that is, particles of starch suspended in water) was boiled, Kirchhoff observed, no change occurred in the starch. When he added a few drops of concentrated acid before boiling the suspension, however, he obtained a very different result. This time, the starch broke down to form glucose, a simple sugar (see Carbohydrates), whereas the acid—which clearly had facilitated the reaction—underwent no change. In 1835 the Swedish chemist Jöns Berzelius (1779–1848) provided a name to the process Kirchhoff had observed: *catalysis,* derived from the Greek words *kata* ("down") and *lyein* ("loosen"). Just two years earlier, in 1833, the French physiologist Anselme Payen (1795–1871) had isolated a material from malt that accelerated the conversion of starch to sugar, for instance, in the brewing of beer.

The renowned French chemist Louis Pasteur (1822–1895), who was right about so many things, called these catalysts *ferments* and pronounced them separate organisms. In 1897, however, the German biochemist Eduard Buchner (1860–1917) isolated the catalysts that bring about the fermentation of alcohol and determined that they were chemical substances, not organisms. By that time, the German physiologist Willy Kahne had suggested the name enzyme for these catalysts in living systems.

Substrates and Active Sites

Each type of enzyme is geared to interact chemically with only one particular substance or type of substance, termed a substrate. The two parts fit together, according to a widely accepted theory introduced in the 1890s by the German chemist Emil Fischer (1852–1919), as a key fits into a lock. Each type of enzyme has a specific three-dimensional shape that enables it to fit with the substrate, which has a complementary shape.

The link between enzymes and substrates is so strong that enzymes often are named after the substrate involved, simply by adding *ase* to the name of the substrate. For example, lactase is the enzyme that catalyzes the digestion of lactose, or milk sugar, and urease catalyzes the chemical breakdown of urea, a substance in urine. Enzymes bind their reactants or substrates at special folds and clefts, named *active sites,* in the structure of the substrate. Because numerous interactions are required in their work of catalysis, enzymes must have many active sites, and therefore they are very large, having atomic mass figures as high as one million amu. (An atomic mass unit, or amu, is approximately equal to the mass of a proton, a positively charged particle in the nucleus of an atom.)

Suppose a substrate molecule, such as a starch, needs to be broken apart for the purposes of digestion in a living body. The energy needed to break apart the substrate is quite large, larger than is available in the body. An enzyme with the correct molecular shape arrives on the scene and attaches itself to the substrate molecule, forming a chemical bond within it. The formation of these bonds causes the breaking apart of other bonds within the substrate molecule, after which the enzyme, its work finished, moves on to another uncatalyzed substrate molecule.

Coenzymes

All enzymes belong to the protein family, but many of them are unable to participate in a catalytic reaction until they link with a nonprotein component called a coenzyme. This can be a medium-size molecule called a prosthetic group, or it can be a metal ion (an atom with a net electric charge), in which case it is known as a cofactor. Quite often, though, coenzymes are composed wholly or partly of vitamins. Although some enzymes are attached very tightly to their coenzymes, others can be parted easily; in either case, the parting almost always deactivates both partners.

The first coenzyme was discovered by the English biochemist Sir Arthur Harden (1865–1940) around the turn of the nineteenth century. Inspired by Buchner, who in 1897 had detected an active enzyme in yeast juice that he had named zymase, Harden used an extract of yeast in most of his studies. He soon discovered that even after boiling, which presumably destroyed the enzymes in yeast, such deactivated yeast could be reactivated. This finding led Harden to the realization that a yeast enzyme appar-



The conversion of cabbage to sauerkraut utilizes a particular bacterium that assists in fermentation. Here workers spread salt and pack chopped cabbage in barrels, where it will ferment for four weeks. *(© Bettmann/Corbis. Reproduced by permission.)*

ently consists of two parts: a large, molecular portion that could not survive boiling and was almost certainly a protein and a smaller portion that had survived and was probably not a protein. Harden, who later shared the 1929 Nobel Prize in chemistry for this research, termed the nonprotein a coferment, but others began calling it a coenzyme.

Real-Life Applications

The Body, Food, and Digestion

Enzymes enable the many chemical reactions that are taking place at any second inside the body of a plant or animal. One example of an enzyme is cytochrome, which aids the respiratory system by catalyzing the combination of oxygen with hydrogen within the cells. Other enzymes facilitate the conversion of food to energy and make possible a variety of other necessary biological functions. Enzymes in the human body fulfill one of three basic functions. The largest of all enzyme types, sometimes called metabolic enzymes, assist in a wide range of basic bodily processes, from breathing to thinking. Some such enzymes are devoted to maintaining the immune system, which protects us against disease, and others are involved in controlling the effects of toxins, such as tobacco smoke, converting them to forms that the body can expel more easily.

A second category of enzyme is in the diet and consists of enzymes in raw foods that aid in the process of digesting those foods. They include proteases, which implement the digestion of protein; lipases, which help in digesting lipids or fats; and amylases, which make it possible to digest carbohydrates. Such enzymes set in motion the digestive process even when food is still in the mouth. As these enzymes move with the food into the upper portion of the stomach, they continue to assist with digestion.

The third group of enzymes also is involved in digestion, but these enzymes are already in the body. The digestive glands secrete juices containing enzymes that break down nutrients chemically into smaller molecules that are more easily absorbed by the body. Amylase in the saliva begins the process of breaking down complex carbohydrates into simple sugars. While food is still in the mouth, the stomach begins producing pepsin, which, like protease, helps digest protein.

Later, when food enters the small intestine, the pancreas secretes pancreatic juice—which contains three enzymes that break down carbohydrates, fats, and proteins—into the duodenum, which is part of the small intestine. Enzymes from food wind up among the nutrients circulated to the body through plasma, a watery liquid in which red blood cells are suspended. These enzymes in the blood assist the body in everything from growth to protection against infection.

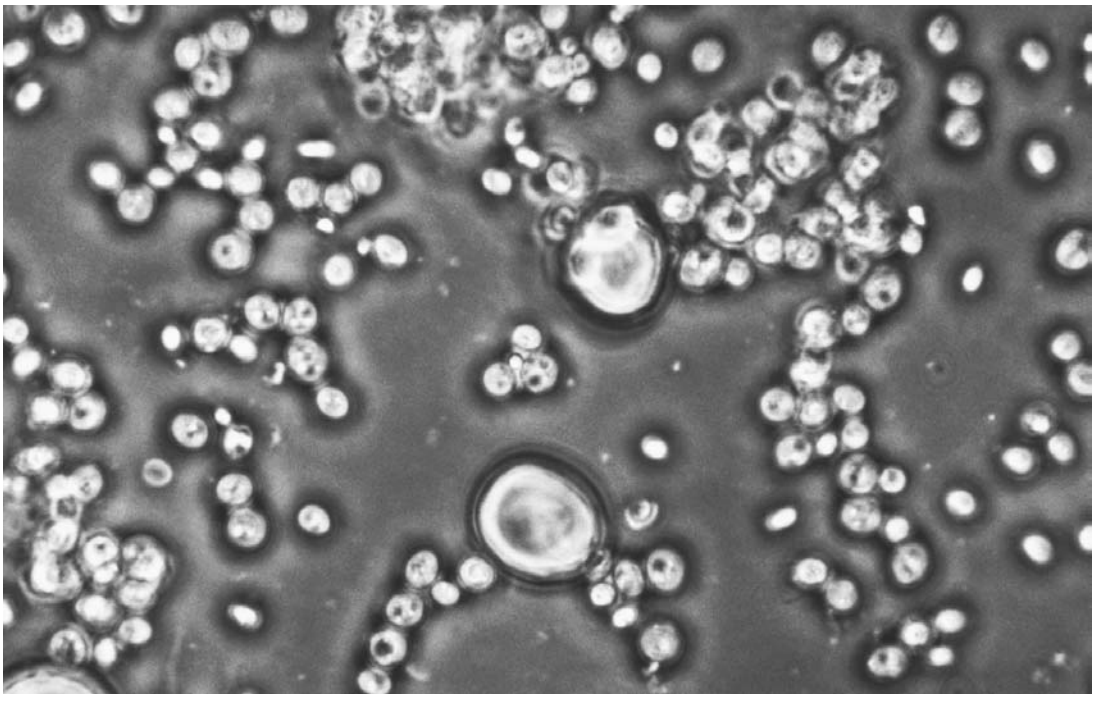
One digestive enzyme that should be in the body, but is not always present, is lactase. As we noted earlier, lactase works on lactose, the principal carbohydrate in milk, to implement its digestion. If a person lacks this enzyme, consuming dairy products may cause diarrhea, bloating, and cramping. Such a person is said to be "lactose intolerant," and if he or she is to consume dairy products at all, they must be in forms that contain lactase. For this reason, Lactaid milk is sold in the specialty dairy section of major supermarkets, while many health-food stores sell lactaid tablets.

Fermentation

Fermentation, in its broadest sense, is a process involving enzymes in which a compound rich in energy is broken down into simpler substances. It also is sometimes identified as a process in which large organic molecules (those containing hydrogen and carbon) are broken down into simpler molecules as the result of the action of microorganisms working anaerobically, or in the absence of oxygen. The most familiar type of fermentation is the conversion of sugars and starches to alcohol by enzymes in yeast. To distinguish this reaction from other kinds of fermentation, the process is sometimes termed *alcoholic* or *ethanolic* fermentation.

At some point in human prehistory, humans discovered that foods spoil, or go bad. Yet at the dawn of history—that is, in ancient Sumer and Egypt—people found that sometimes the "spoilage" (that is, fermentation) of products could have beneficial results. Hence the fermentation of fruit juices, for example, resulted in the formation of primitive forms of wine. Over the centuries that followed, people learned how to make both alcoholic beverages and bread through the controlled use of fermentation.

Alcoholic beverages. In fermentation, starch is converted to simple sugars, such as sucrose and glucose, and through a complex sequence of some 12 reactions, these sugars then are converted to ethyl alcohol (the kind of alcohol that can be consumed, as opposed to methyl alcohol and other toxic forms) and carbon dioxide. Numerous enzymes are needed to carry out this sequence of reac-



Baker's yeast, single-cell fungi that produce carbon dioxide in the oxidation of sugar. Carbon dioxide causes bread to rise when yeast is mixed into dough, a result of the fermentation of the sugar by enzymes in the yeast. *(© Lester V. Bergman/Corbis. Reproduced by permission.)*

tions, the most important being zymase, which is found in yeast cells. These enzymes are sensitive to environmental conditions, such that when the concentration of alcohol reaches about 14%, they are deactivated. For this reason, no fermentation product (such as wine) can have an alcoholic concentration of more than about 14%. Stronger alcoholic beverages, such as whisky, are the result of another process, distillation.

The alcoholic beverages that can be produced by fermentation vary widely, depending primarily on two factors: the plant that is fermented and the enzymes used for fermentation. Depending on the materials available to them, various peoples have used grapes, berries, corn, rice, wheat, honey, potatoes, barley, hops, cactus juice, cassava roots, and other plant materials for fermentation to produce wines, beers, and other fermented drinks. The natural product used in making the beverage usually determines the name of the synthetic product. Thus, for instance, wine made with rice—a time-honored tradition in Japan—is known as sake, while a fermented beverage made from barley, hops, or malt sugar has a name very familiar to Americans: beer. Grapes make wine, but "wine" made from honey is known as mead.

OTHER FOODS. Of course, ethyl alcohol is not the only useful product of fermentation or even of fermentation using yeast; so, too, are baked goods, such as bread. The carbon dioxide generated during fermentation is an important component of such items. When the batter for bread is mixed, a small amount of sugar and yeast is added. The bread then rises, which is more than just a figure of speech: it actually puffs up as a result of the fermentation of the sugar by enzymes in the yeast, which brings about the formation of carbon dioxide gas. The carbon dioxide gives the batter bulkiness and texture that would be lacking without the fermentation process. Another food-related application of fermentation is the production of one processed type of food from a raw, natural variety. The conversion of raw olives to the olives sold in stores, of cucumbers to pickles, and of cabbage to sauerkraut utilizes a particular bacterium that assists in a type of fermentation.

INDUSTRIAL APPLICATIONS. There is even ongoing research into the creation of edible products from the fermentation of petroleum. While this may seem a bit far-fetched, it is less difficult to comprehend powering cars with an environmentally friendly product of fer-

KEY TERMS

ACTIVATION ENERGY: A threshold that must be crossed to facilitate a chemical reaction. There are three ways to reach the activation energy: by increasing the concentration of reactants, by raising their temperature, or by introducing a catalyst, such as an enzyme.

ACTIVE SITES: Folds and clefts on the surface of an enzyme that enable attachment to its particular substrate.

AMINO ACIDS: Organic compounds made of carbon, hydrogen, oxygen, nitrogen, and (in some cases) sulfur bonded in characteristic formations. Strings of amino acids make up proteins.

BIOCHEMISTRY: The area of the biological sciences concerned with the chemical substances and processes in organisms.

CARBOHYDRATES: Naturally occurring compounds, consisting of carbon, hydrogen, and oxygen, whose primary function in the body is to supply energy. Included in the carbohydrate group are sugars, starches, cellulose, and various other substances. Most carbohydrates are produced by green plants in the process of undergoing photosynthesis.

CATALYSIS: The act or process of catalyzing, or speeding up the rate of reaction between substances.

CATALYST: A substance that speeds up a chemical reaction without participating in it. Catalysts, of which enzymes are a good example, thus are not consumed in the reaction.

COENZYME: A nonprotein component sometimes required to allow an enzyme to set in motion a catalytic reaction.

ENZYME: A protein that acts as a catalyst, a material that speeds up chemical reactions in the bodies of plants and animals without itself taking part in, or being consumed by, these reactions.

FERMENTATION: A process involving enzymes in which a compound rich in energy is broken down into simpler substances.

METABOLISM: The chemical process by which nutrients are broken down and converted into energy or are used in the construction of new tissue or other material in the body.

MOLECULE: A group of atoms, usually but not always representing more than one element, joined in a structure. Compounds typically are made up of molecules.

ORGANIC: At one time, chemists used the term *organic* only in reference to living things. Now the word is applied to compounds containing carbon and hydrogen.

PROTEINS: Large molecules built from long chains of 50 or more amino acids. Proteins serve the functions of promoting normal growth, repairing damaged tissue, contributing to the body's immune system, and making enzymes.

REACTANT: A substance that interacts with another substance in a chemical reaction, resulting in the formation of a chemical or chemicals known as the *product.*

STARCHES: Complex carbohydrates without taste or odor, which are granular or powdery in physical form.

SUBSTRATE: A reactant that typically is paired with a particular enzyme.

KEY TERMS CONTINUED

Enzymes often are named after their respective substrates by adding the suffix *ase* (e.g., the enzyme lactase is paired with the substrate lactose).

SUGARS: One of the three principal types of carbohydrate, along with starches and cellulose. Sugars can be defined as any of various water-soluble carbohydrates of varying sweetness. What we think of as "sugar" (i.e., table sugar) is actually sucrose.

VITAMINS: Organic substances that, in extremely small quantities, are essential to the nutrition of most animals and some plants. In particular, vitamins work with enzymes in regulating metabolic processes; however, they do not in themselves provide energy, and thus vitamins alone do not qualify as a form of nutrition.

mentation known as gasohol. Gasohol first started to make headlines in the 1970s, when an oil embargo and resulting increases in gas prices, combined with growing environmental concerns, raised the need for a type of fuel that would use less petroleum. A mixture of about 90% gasoline and 10% alcohol, gasohol burns more cleanly that gasoline alone and provides a promising method for using renewable resources (plant material) to extend the availability of a nonrenewable resource (petroleum). Furthermore, the alcohol needed for this product can be obtained from the fermentation of agricultural and municipal wastes.

The applications of fermentation span a wide spectrum, from medicines that go into people's bodies to the cleaning of waters containing human waste. Some antibiotics and other drugs are prepared by fermentation: for example, cortisone, used in treating arthritis, can be made by fermenting a plant steroid known as diosgenin. In the treatment of wastewater, anaerobic, or non-oxygen-dependent, bacteria are used to ferment organic material. Thus, solid wastes are converted to carbon dioxide, water, and mineral salts.

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METABOLISM

METABOLISM
DIGESTION
RESPIRATION

METABOLISM

CONCEPT

The term metabolism refers to all of the chemical reactions by which complex molecules taken into an organism are broken down to produce energy and by which energy is used to build up complex molecules. All metabolic reactions fall into one of two general categories: catabolic and anabolic reactions, or the processes of breaking down and building up, respectively. The best example of metabolism from daily life occurs in the process of taking in and digesting nutrients, but sometimes these processes become altered, either through a person's choice or through outside factors, and metabolic disorders follow. Such disorders range from anorexia and bulimia to obesity. These are all examples of an unhealthy, unnatural alteration to the ordinary course of metabolism; on the other hand, hibernation allows animals to slow down their metabolic rates dramatically as a means of conserving energy during times when food is scarce.

HOW IT WORKS

The Body's Furnace

The term metabolism, strangely enough, is related closely to devil, with which it shares the Greek root *ballein,* meaning "to throw." By adding *dia* ("through" or "across"), one arrives at devil and many related words, such as diabolical; on the other hand, the replacement of that prefix with *meta* ("after" or "beyond") yields the word metabolism. The connection between the two words has been obscured over time, but it might be helpful to picture metabolism in terms of an image that goes with that of a devil: a furnace.

Metabolism is indeed like a furnace, in that it burns energy, and that is the aspect most commonly associated with this concept. But metabolism also involves a function that a furnace does not: building new material. All metabolic reactions can be divided into either catabolic or anabolic reactions. Catabolism is the process by which large molecules are broken down into smaller ones with the release of energy, whereas anabolism is the process by which energy is used to build up complex molecules needed by the body to maintain itself and develop new tissue.

DIGESTION. One way to understand the metabolic process is to follow the path of a typical nutrient as it passes through the body. The digestive process is discussed in Digestion, while nutrients are examined in Nutrients and Nutrition as well as in Proteins, Amino Acids, Enzymes, Carbohydrates, and Vitamins. Here we touch on the process only in general terms, as it relates to metabolism.

The term digestion is not defined in the essay on that subject, because it is an everyday word whose meaning is widely known. For the present purposes, however, it is important to identify it as the process of breaking down food into simpler chemical compounds as a means of making nutrients absorbable by the body. This is a catabolic process, because the molecules of which foods are made are much too large to pass through the lining of the digestive system and directly into the bloodstream. Thanks to the digestive process, smaller molecules are formed and enter the bloodstream, from whence they are carried to individual cells throughout a person's body.

The smaller molecules into which nutrients are broken down make up the metabolic pool, which consists of simpler substances.The metabolic pool includes simple sugars, made by the breakdown of complex carbohydrates; glycerol and fatty acids, which come from the conversion of lipids, or fats; and amino acids, formed by the breakdown of proteins. Substances in the metabolic pool provide material from which new tissue is constructed—an anabolic process.

The chemical breakdown of substances in the cells is a complex and wondrous process. For instance, a cell converts a sugar molecule into carbon dioxide and water over the course of about two dozen separate chemical reactions. This is what cell biologists call a metabolic pathway: an orderly sequence of reactions, with particular enzymes (a type of protein that speeds up chemical reactions) acting at each step along the way. In this instance, each chemical reaction makes a relatively modest change in the sugar molecule—for example, the removal of a single oxygen atom or a single hydrogen atom—and each is accompanied by the release of energy, a result of the breaking of chemical bonds between atoms.

ATP AND ADP

Cells capture and store the energy released in catabolic reactions through the use of chemical compounds known as energy carriers. The most significant example of an energy carrier is adenosine triphosphate, or ATP, which is formed when a simpler compound, adenosine diphosphate (ADP), combines with a phosphate group. (A phosphate is a chemical compound that contains oxygen bonded to phosphorus, and the term *group* in chemistry refers to a combination of atoms from two or more elements that tend to bond with other elements or compounds in certain characteristic ways.)

ADP will combine with a phosphate group only if energy is added to it. In cells, that energy comes from the catabolism of compounds in the metabolic pool, including sugars, glycerol (related to fats), and fatty acids. The ATP molecule formed in this manner has taken up the energy previously stored in the sugar molecule, and thereafter, whenever a cell needs energy for some process, it can obtain it from an ATP molecule. The reverse of this process also takes place inside cells. That is, energy from an ATP molecule can be used to put simpler molecules together to make more complex molecules. For example, suppose that a cell needs to repair a rupture in its cell membrane. To do so, it will need to produce new protein molecules, which are made from hundreds or thousands of amino-acid molecules. These molecules can be obtained from the metabolic pool.

The reactions by which a compound is metabolized differ for various nutrients. Also, energy carriers other than ATP may play a part. For example, the compound known as nicotinamide adenine dinucleotide phosphate (NADPH) also has a role in the catabolism and anabolism of various substances. The general outline described here, however, applies to all metabolic reactions.

CATABOLISM AND ANABOLISM

Energy released from organic nutrients (those containing carbon and hydrogen) during catabolism is stored within ATP, in the form of the high-energy chemical bonds between the second and third molecules of phosphate. The cell uses ATP for synthesizing cell components from simple precursors, for the mechanical work of contraction and motion, and for transport of substances across its membrane. ATP's energy is released when this bond is broken, turning ATP into ADP. The cell uses the energy derived from catabolism to fuel anabolic reactions that synthesize cell components. Although anabolism and catabolism occur simultaneously in the cell, their rates are controlled independently. Cells separate these pathways because catabolism is a "downhill" process, or one in which energy is released, while anabolism is an "uphill" process requiring the input of energy.

Catabolism and anabolism share an important common sequence of reactions known collectively as the citric acid cycle, the tricarboxylic acid cycle, or the *Krebs cycle.* Named after the German-born British biochemist Sir Hans Adolf Krebs (1900–1981), the Krebs cycle is a series of chemical reactions in which tissues use carbohydrates, fats, and proteins to produce energy; it is part of a larger series of enzymatic reactions known as oxidative phosphorylation. In the latter reaction, glucose is broken down to release energy, which is stored in the form of ATP—a catabolic sequence. At the same time, other molecules produced by the Krebs cycle are used as

precursor molecules for reactions that build proteins, fats, and carbohydrates—an anabolic sequence. (A precursor is a substance, cellular component, or cell from which another substance, cellular component, or cell—different in kind from the precursor—is formed.)

Introduction to Lipids

As noted earlier, many practical aspects of metabolism are discussed elsewhere, particularly in the essays Digestion and Nutrients and Nutrition. Also, two types of chemical compound, proteins and carbohydrates, are so important to a variety of metabolic processes that they are examined in detail within entries of their own. In the present context, let us focus on the third major kind of nutrient, lipids or fats.

Lipids are soluble in nonpolar solvents, which is the reason why a gravy stain or other grease stain is difficult to remove from clothing without a powerful detergent or spot remover. Water molecules are polar, because the opposing electric charges tend to occupy opposite sides or ends of the molecule. In a molecule of oil, whether derived from petroleum or from animal or vegetable fat, electric charges are very small, and are distributed evenly throughout the molecule.

Whereas water molecules tend to bond relatively well, like a bunch of bar magnets attaching to one another at their opposing poles, oil and fat molecules tend not to bond. (The "bond" referred to here is the fairly weak one between molecules. Much stronger is the chemical bond *within* molecules—a bond that, when broken, brings about a release of energy, as noted earlier.) Their functions are as varied as their structures, but because they are all fat-soluble, lipids share in the ability to approach and even to enter cells. The latter have membranes that, while highly complex in structure, can be identified in simple terms as containing lipids or lipoproteins (lipids attached to proteins). The behavior of lipids and lipid-like molecules, therefore, becomes very important in understanding how a substance may or may not enter a cell. Such a substance may be toxic, as in the case of some pesticides, but if they are lipid-like, they are able to penetrate the cell's membrane. (See Food Webs for more about the biomagnification of DDT.)

In addition to lipoproteins, there are glycolipids, or lipids attached to sugars, as well as lipids attached to alcohols and some to phosphoric acids. The attachment with other compounds greatly alters the behavior of a lipid, often making them bipolar—that is, one end of the molecule is water-soluble. This is important, because it allows lipids to move out of the intestines and into the bloodstream. In the digestive process, lipids are made water-soluble either by being broken down into smaller parts or through association with another substance. The breaking down usually is done via two different processes: hydrolysis, or chemical reaction with water, and saponification. The latter, a reaction in which certain kinds of organic compounds are hydrolyzed to produce an alcohol and a salt, is used in making soap.

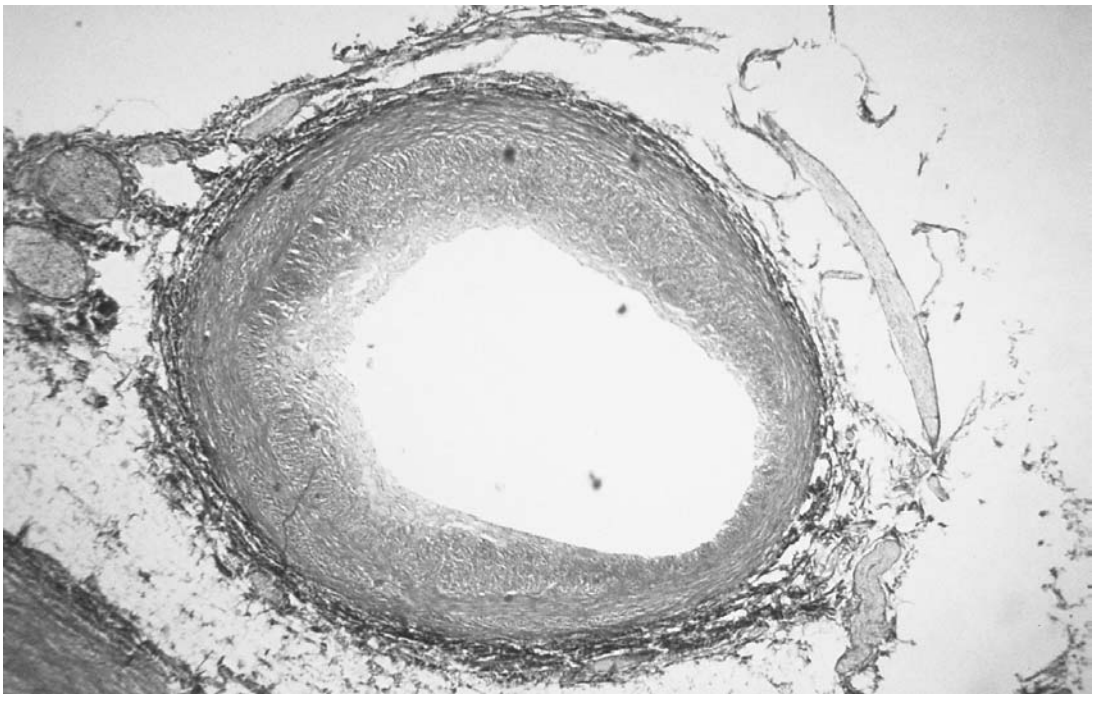
REAL-LIFE APPLICATIONS

Putting Lipids to Use

Derived from living systems of plants, animals, or humans, lipids are essential to good health, not only for humans but also for other animals and even plants. Seeds, for example, contain lipids for the storage of energy. Because fat is a poor conductor of heat, lipids also can function as effective insulators, and for this reason, people living in Arctic zones seek fatty foods such as blubber. Some lipids function as chemical messengers in the body, while others serve as storage areas for chemical energy. There is a good reason why babies are born with "baby fat" and why children entering puberty often tend to become chubby: in both cases, they are building up energy reserves for the great metabolic hurdles that lie ahead, and within a few years, they will have used up those excessive fat stores.

FATS AND OILS. Fats and oils are both energy-rich compounds that are basic components of the normal diet. Both have essentially the same chemical structure—a mixture of fatty acids combined with glycerol—and are insoluble (do not dissolve) in water. While fats remain solid or at least semisolid at room temperature, however, most oils very quickly become liquid at increased temperatures. Animal fats and oils include butter, lard, tallow, and fish oil. Numerous other oils, such as cottonseed, peanut, and corn oils, are derived from plants.

Fats have two main functions: they provide some of the raw material for synthesizing (creat-



Cross-section micrograph of a blood vessel with atherosclerotic lesion, composed of cholesterol and other lipids. High levels of certain circulating fats can lead to a thickening of the artery walls and have been linked to various illnesses, including heart disease and cancer. *(© Lester V. Bergman/Corbis. Reproduced by permission.)*

ing) and repairing tissues, and they serve as a concentrated source of fuel energy. Fats, in fact, provide humans with roughly twice as much energy, per unit weight, as carbohydrates and proteins. Fats are not only an important source of day-to-day energy, but they also can be stored indefinitely as adipose (fat) tissue in case of future need. Fats also help by transporting fat-soluble vitamins, such as A and D (see Vitamins), throughout the system. They cushion and form protective pads around delicate organs, such as the heart, liver and kidneys, and the layer of fat under the skin helps insulate the body against too much heat loss. They even add to the flavor of foods that might otherwise be inedible.

NOT ALL FAT IS CREATED EQUAL. Although normal amounts of certain kinds of fat in the diet are essential to good health, unnecessarily high amounts (especially of unhealthy fats) can lead to various problems. Healthy fats include those from fatty fish, such as salmon, mackerel, or tuna, or from fat-containing vegetables, such as the avocado. In addition, many vegetable oils, particularly olive oil, can be beneficial.

Bad fats, on the other hand, are usually ones that have been tampered with through a process known as hydrogenation. This is a term describing any chemical reaction in which hydrogen atoms are added to fill in chemical bonds between carbon and other atoms, but in the case of fatty foods, hydrogenation involves the saturation of hydrocarbons, organic chemical compounds whose molecules are made up of nothing but carbon and hydrogen atoms. When they are treated with hydrogen gas, they become "saturated" with hydrogen atoms. Saturated fats, as they are called, are harder and more stable and stand up better to the heat of frying, which makes them more desirable for use in commercial products. For this reason, many foods contain hydrogenated vegetable oil; however, saturated fats have been linked to a rise in blood cholesterol levels—and to an increased risk of heart disease.

Cholesterol is a variety of lipid, and, like other lipids, some of it is essential—but only some and only of the right kind. Most cholesterol is transported through the blood in low-density lipoproteins, or LDLs, which have been nicknamed *bad cholesterol.* These lipoproteins are received by LDL receptors on the cell mem-

branes, but if there are more LDLs than LDL receptors, the excess LDLs will be deposited in the arteries. Thus, LDLs are not really "bad" unless there are too many of them. On the other hand, "good" cholesterol (HDLs, or high-density lipoproteins) help protect against damage to the artery walls by carrying excess LDLs back to the liver.

HOW MUCH IS TOO MUCH? A certain amount of excess adipose tissue can be valuable during periods of illness, overactivity, or food shortages. Too much, however, can be unsightly and also can overwork the heart and put added stress on other parts of the body. High levels of certain circulating fats may lead to atherosclerosis, which is a thickening of the artery walls, and they have been linked to various illnesses, including cancer.

With fat, as with many things where the body is concerned, if a little is a good, this does not mean that a lot is better. In the past, nutritionists considered a diet that obtained 40% of its calories from fats a reasonable one; today, however, they recommend that no more than 30% of all calories (and preferably an even smaller percentage) come from fat. Agreement on this point, however, is far from universal. Some physicians and scientists maintain that dietary fat does not contribute as much to body fat as do carbohydrates. Carbohydrates are good for someone who needs a boost of energy that can be consumed easily by the body, such as an athlete going into competition. But for inactive people—and this includes a large portion of Americans—carbohydrates simply are stored as fat.

Experts do not even agree on the answer to a question much simpler than "How much is too much fat in the diet?"—the question "How much is too much fat on the body?" Some doctors classify a person as obese whose weight is at least 20% more than the recommended weight for his or her height, but others say that standard height-and-weight charts are misleading. After all, muscle weighs more than fat, and it is conceivable that a very muscular athlete with very little body fat might qualify as "overweight" compared with the recommended weight for his or her height.

BODY FAT, THE SEXES, AND NATURE. Because of the complexity of the issue, many experts contend that the proportion of fat to muscle, measured by the skinfold "pinch" test, is a better measure of obesity. (Being obese is not the same as being overweight: the muscular athlete described in the last paragraph is *overweight* but not *obese,* a term that implies an excess of body fat.) In healthy adults, fat typically should account for about 18–25% of the body weight in females and 15–20% in males.

The reason for the difference between men and women is that fat naturally accumulates in a woman's buttocks and thighs, because nature "assumes" that she will bear children, in which case such excess fat will be useful. This is why women over the age of about 25 often complain that when they and their husbands or boyfriends embark on a fitness program together, the men usually see results faster. The reason is that there is no genetic or evolutionary benefit to be gained from a man having fat around his waist, which is where men usually gain. If anything—since our genetic codes and makeup have changed little since prehistory—the well-being and propagation of the human species are best served by a lean, muscular male capable of killing animals to feed and protect his family. All of this means, of course, that men should not gloat if they see better results from a regular workout program; instead, they should just recognize that nature is at work in their wives' or girlfriends' bodies as in their own.

Metabolic Disorders

Enzymes, as we noted earlier, are critical participants in metabolic reactions. They are like relay runners in a race, in this case a race along the metabolic pathways whereby nutrients are turned into energy or new bodily material. Therefore, if an enzyme is missing or does not function as it should, it can create a serious metabolic disorder. An example is phenylketonuria (PKU), caused by the lack of an enzyme known as phenylalanine hydroxylase. This enzyme is responsible for converting the amino acid phenylalanine to a second amino acid, tyrosine; when this does not happen, phenylalanine builds up in the body. It is converted to a compound called phenylpyruvate, which impairs normal brain development, resulting in severe mental retardation.

Other examples of metabolic disorders include alkaptonuria, thalassemia, porphyria, Tay-Sachs disease, Hurler syndrome, Gaucher disease, galactosemia, Cushing syndrome, dia-



Diana, the late Princess of Wales, suffered from bulimia, a disorder that prompts a person to go on eating binges and then "purge," either by vomiting or by taking large amounts of laxatives. *(© Corbis. Reproduced by permission.)*

betes mellitus, hyperthyroidism, and hypothyroidism. Most of these conditions affect a small population; however, diabetes mellitus (discussed in Noninfectious Diseases) is one of the leading killers in America. At present, no cures for metabolic disorders exist. The best approach is to diagnose such conditions as early as possible and then arrange a person's diet to deal as effectively as possible with that disorder.

Eating Disorders

Eating disorders are a different matter, because they are psychological rather than physiological conditions. No one is sure what causes eating disorders, but researchers think that family dynamics, biochemical abnormalities, and modern American society's preoccupation with thinness all may contribute. Eating disorders are virtually unknown in parts of the world where food is scarce, but in wealthy lands, such as the United States, problems of overeating, self-induced starvation, or forced purging have gained considerable attention.

Anorexia nervosa, bulimia, and obesity are the most well known types of eating disorder. The word *anorexia* comes from the Greek for "lack of appetite," but the problem for people with anorexia is not that they are not hungry. On the contrary, they are starving, but unlike poor people in the Third World, they are not starving as the result of a shortage of food but because they are denying themselves nutrition. They do this because they fear gaining weight, even when they are so severely underweight that they look like skeletons.

The name of a related condition, *bulimia,* literally means "hungry as an ox." People with this problem go on eating binges, often gorging on junk food. Then they force their bodies to get rid of the food, either by vomiting or by taking large amounts of laxatives. A third type of eating disorder, obesity, also is characterized by uncontrollable overeating, but in this case the person does not force the body to eject the food that has been consumed. That, at least, makes obesity more healthy than bulimia, but there is nothing healthy about accumulating vast amounts of body fat, as severely obese people do.

Anorexia and bulimia. Young people are more likely than older people to suffer anorexia or bulimia, conditions that typically become apparent at about the age of 20 years. Although both men and women can experience the problem, in fact, only about 5% of people with these eating disorders are male. And though anorexia and bulimia are closely related—particularly inasmuch as they are psychological in origin but can exact a heavy biological toll—there are several important differences.

People who have anorexia or bulemia often come from families with overprotective parents who have unrealistically high expectations of their children. Frequently, high expectations go hand in hand with a wealthy background, and certainly anorexia and bulimia are not conditions that typically affect the poor. Anorexia and bulimia often seem to develop after some stressful experience, such as moving to a new town, changing schools, or going through puberty. Low self-esteem, fear of losing control, and fear of growing up are common characteristics of people with these conditions. Their need for approval manifests in a quest to meet or exceed our culture's idealized concept of extreme thinness. This quest is a part of our popular culture, promoted by waiflike models whose sunken eyes stare out of fashion magazines.

Like anorexia, bulimia results in starvation, but there are behavioral, physical, and psychological differences between the two. Bulimia is both less and more dangerous: on the one hand, people who have it tend to be of normal weight or are overweight, and unlike those with anorexia, they are aware of the fact that they have a problem. On the other hand, because the effects of their behavior are not so readily apparent, it is easier for a person with bulimia to persist in the pattern of bingeing and purging for much longer.

Approximately one in five persons with bulimia has a problem with drug or alcohol use, and they pursue their binges in a way not unlike that of a guilty addict or alcoholic hiding the spent needles or empty bottles from family members. They may go from restaurant to restaurant to avoid being seen eating too much in any one place, or they may pretend to be shopping for a large dinner party when, in fact, they intend to eat all the food themselves. Because of the expense of consuming so much food, some resort to shoplifting.

During a binge, people suffering from bulimia favor high-carbohydrate foods, such as doughnuts, candy, ice cream, soft drinks, cookies, cereal, cake, popcorn, and bread, and they consume many times the number of calories they would normally consume in one day. No matter what their normal eating habits, they tend to eat quickly and messily during a binge, stuffing the food into their mouths and gulping it down, sometimes without even tasting it. Some say they get a feeling of euphoria during binges, similar to the "runner's high" that some people get from exercise. Then, when they have gorged themselves, they force the food back out, either by causing themselves to vomit or by taking large quantities of laxatives.

Regular self-induced vomiting can cause all sorts of physical problems, such as damage to the stomach and esophagus, chronic heartburn, burst blood vessels in the eyes, throat irritation, and erosion of tooth enamel from the acid in vomit. Excessive use of laxatives can induce muscle cramps, stomach pains, digestive problems, dehydration, and even poisoning, while bulimia, in general, brings about vitamin deficiencies and imbalances of critical body fluids, which, in turn, can lead to seizures and kidney failure.

The self-imposed starvation of people with anorexia likewise takes a heavy toll on the body. The skin becomes dry and flaky, muscles begin to waste away, bones stop growing and may become brittle, and the heart weakens. Seeking to protect itself in the absence of proper insulation from fat, the body sprouts downy hair on the face, back, and arms in response to lower body temperature. In women, menstruation stops, and permanent infertility may result. Muscle cramps, dizziness, fatigue, and even brain damage as well as kidney and heart failure are possible. An estimated 10% to 20% of people with anorexia die either as a direct result of starvation or by suicide.

To save people with anorexia, force-feeding may be necessary. Some 70% of anorexia patients who are treated for about six months return to normal body weight, but about 15-20% can be expected to relapse. Bulimia is not as likely as anorexia to reach life-threatening stages, so hospitalization typically is not necessary. Treatment generally calls for psychotherapy and sometimes the administration of antidepressant drugs. Unlike people with anorexia, those with bulimia usually admit they have a problem and want help overcoming it.

OBESITY. Unlike anorexia or bulimia, obesity is more of a problem among people from lower-income backgrounds. This probably relates to a lack of education concerning nutrition, combined with the fact that healthier food is more expensive; by contrast, unhealthy items, such as white sugar, corn meal, and fatty cuts of pork and other meats can fill or overfill a person's stomach inexpensively. In addition, though men and women both tend to gain weight as they age, women are almost twice as likely as men to be obese.

Some cases of obesity relate to metabolic problems, while others stem from compulsive eating, which is psychologically motivated. Some studies suggest that obese people are much more likely than others to eat in response to stress, loneliness, or depression. And just as emotional pain can lead to obesity, obesity can lead to psychological scars. From childhood on, obese people are taunted and shunned, and throughout life they may face discrimination in school and on the job.

Physically, obesity is a killer, especially for those who are morbidly obese—that is, people whose obesity endangers their health. Obesity is



Bears, which we think of as the classic hibernating animal, are actually just deep sleepers. A hibernating animal shows a drastic reduction in metabolism and then awakes relatively slowly, whereas a sleeping animal decreases its metabolism only slightly and can wake up almost instantly if disturbed. *(© Dan Guravich/Corbis. Reproduced by permission.)*

a risk factor for diabetes, high blood pressure, arteriosclerosis, angina pectoralis (chest pains due to inadequate blood flow to the heart), varicose veins, cirrhosis of the liver, and kidney disease. Obese people are about 1.5 times more likely to have heart attacks than are other people, and the overall death rate among people ages 20-64 is 50% higher for the obese than for people of ordinary weight.

Hibernation

Having looked at several unnatural ways in which people alter their metabolisms, let us close with an example of a very natural way that animals sometimes temporarily change theirs. This is hibernation, a state of inactivity in which an animal's heart rate, body temperature, and breathing rate are decreased as a way to conserve energy through the cold months of winter. A similar state, known as estivation, is adopted by some desert animals during the dry months of summer.

Hibernation is a technique that animals have developed, as a result of natural selection over the generations (see Evolution), to adapt to harsh environmental conditions. When food is scarce, a nonhibernating animal would be like a business operating at a loss—that is, using more energy maintaining its body temperature and searching for food than it would receive from consuming the food. Hibernating animals use 70-100 times less energy than when they are active, allowing them to survive until food is once again plentiful.

Contrast with sleep. Many animals sleep more often when food is scarce, but only a few truly hibernate. Bears, which many people think of as the classic hibernating animal, are actually just deep sleepers. By contrast, true hibernation occurs only in small mammals, such as bats and woodchucks and a few birds, among them nighthawks. Some insects also practice a form of hibernation. Hibernation differs from sleep, in that a hibernating animal shows a drastic reduction in metabolism and then awakes relatively slowly, whereas a sleeping animal decreases its metabolism only slightly and can wake up almost instantly if disturbed. Also, hibernating animals do not show periods of rapid eye movement (REM), the stage of sleep associated with dreaming in humans.

The process of hibernation. Animals prepare for hibernation in the

KEY TERMS

ADIPOSE: Of or relating to animal fat.

AMINO ACIDS: Organic compounds made of carbon, hydrogen, oxygen, nitrogen, and (in some cases) sulfur bonded in characteristic formations. Strings of amino acids make up proteins.

ANABOLISM: The metabolic process by which energy is used to build up complex molecules that the body needs to maintain itself and develop new material.

ATOM: The smallest particle of an element, consisting of protons, neutrons, and electrons. An atom can exist either alone or in combination with other atoms in a molecule.

ATP: Adenosine triphosphate, an energy carrier formed when a simpler compound, adenosine diphosphate (ADP), combines with a phosphate group.

BLOOD SUGAR: The glucose in the blood.

CARBOHYDRATES: Naturally occurring compounds, consisting of carbon, hydrogen, and oxygen, whose primary function in the body is to supply energy. Included in the carbohydrate group are sugars, starches, cellulose, and various other substances. Most carbohydrates are produced by green plants in the process of undergoing photosynthesis.

CATABOLISM: The metabolic process by which large molecules are broken down into smaller ones with the release of energy. Compare with *anabolism.*

COMPOUND: A substance in which atoms of more than one element are bonded chemically to one another.

DIGESTION: The process of breaking food down into simpler chemical compounds as a means of making the nutrients absorbable by the body or organism.

ENZYME: A protein material that speeds up chemical reactions in the bodies of plants and animals without itself taking part in, or being consumed by, these reactions.

GLUCOSE: A monosaccharide (sugar) that occurs widely in nature and which is the form in which animals usually receive carbohydrates. Also known as *dextrose, grape sugar,* and *corn sugar.* See also *blood sugar.*

HYDROCARBON: Any organic chemical compound whose molecules are made up of nothing but carbon and hydrogen atoms.

LIPIDS: Fats and oils, which dissolve in oily or fatty substances but not in water-based liquids. In the body, lipids supply energy in slow-release doses, protect organs from shock and damage, and provide insulation for the body, for instance from toxins.

METABOLIC PATHWAY: An orderly sequence of reactions, with particular enzymes acting at each step along the way. Metabolic pathways may be either linear or circular, and sometimes they are linked, meaning that the product of one pathway becomes a reactant in another.

METABOLIC POOL: A group of relatively simple substances (e.g., amino acids) formed by the breakdown of relatively complex nutrients.

METABOLISM: The chemical process by which nutrients are broken down and converted into energy or are used in the

KEY TERMS CONTINUED

construction of new tissue or other material in the body. All metabolic reactions are either catabolic or anabolic.

MOLECULE: A group of atoms, usually but not always representing more than one element, joined in a structure. Compounds typically are made up of molecules.

NUTRIENT: Materials essential to the survival of organisms. They include proteins, carbohydrates, lipids (fats), vitamins, and minerals.

NUTRITION: The series of processes by which an organism takes in nutrients and makes use of them for its survival, growth, and development. The term *nutrition* also can refer to the study of nutrients, their consumption, and their use in the organism's body.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to compounds containing carbon and hydrogen.

PHOSPHATE GROUP: A group (that is, a combination of atoms from two or more elements that tend to bond with other elements or compounds in certain characteristic ways) that includes a phosphate, or a chemical compound that contains oxygen bonded to phosphorus.

PRODUCT: A substance or substances formed from the interaction of reactants in a chemical reaction.

PROTEINS: Large molecules built from long chains of 50 or more amino acids. Proteins serve the functions of promoting normal growth, repairing damaged tissue, contributing to the body's immune system, and making enzymes.

REACTANT: A substance that interacts with another substance in a chemical reaction, resulting in the formation of a chemical or chemicals known as the *product(s)*.

SUGARS: One of the three principal types of carbohydrate, along with starches and cellulose. Sugars can be defined as any of various water-soluble carbohydrates of varying sweetness. What we think of as "sugar" (i.e., table sugar) is actually sucrose; "blood sugar," on the other hand, is glucose.

TISSUE: A group of cells, along with the substances that join them, that forms part of the structural materials in plants or animals.

fall by storing food; usually this storage is internal, in the form of fat reserves. A woodchuck in early summer may have only about 5% body fat, but as fall approaches, changes in the animal's brain chemistry cause it to feel hungry and to eat constantly. As a result, the woodchuck's body fat increases to about 15% of its total weight. In other animals, such as the dormouse, fat may constitute as much as 50% of the animal's weight by the time hibernation begins. A short period of fasting follows the feeding frenzy, to ensure that the digestive tract is emptied completely before hibernation begins.

Going into hibernation is a gradual process. Over a period of days, an animal's heart rate and breathing rate drop slowly, eventually reaching rates of just a few beats or breaths per minute. Their body temperatures also drop from levels of about 100°F (38°C) to about 60°F (15°C). The lowered body temperature makes fewer demands on metabolism and food stores. Electric activity in the brain ceases almost completely during

hibernation, although some areas—those that respond to external stimuli, such as light, temperature, and noise—remain active. Thus, the hibernating animal can be aroused under extreme conditions.

Periodically—perhaps every two weeks or so—the hibernating animal awakes and takes a few deep breaths to refresh its air supply. If the weather is particularly mild, some animals may venture from their lairs. An increase in heart rate signals that the time for arousal, or ending hibernation, is near. Blood vessels dilate, particularly around the heart, lungs, and brain, and this leads to an increased breathing rate. Eventually, the increase in circulation and metabolic activity spreads throughout the body, and the animal resumes a normal waking state.

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DIGESTION

CONCEPT

Digestion is the process whereby the foods we eat pass through our bodies and are directed toward the purposes of either providing the body with energy or building new cellular material, such as fat or muscle. The parts of food that the body cannot use, along with other wastes from the body, are eliminated in the form of excrement. Aspects of digestion, particularly the production of waste and intestinal gas, are not exactly topics for polite conversation, yet without these and other digestive processes, life for humans and other organisms would be impossible. The functioning of digestion itself is like that of a well-organized, cohesive sports team or even of a symphony orchestra: there are many parts and players, each with an indispensable role.

HOW IT WORKS

Nutrients

For digestion to occur, of course, it is necessary first to have something to digest—namely, nutrients. What follows is a cursory overview of nutrients and nutrition, subjects covered in much more depth within the essay of that name. Nutrients include proteins, carbohydrates, fats, minerals, and vitamins. In addition to these nutrients, animal life requires other materials, not usually considered nutrients, which include water, oxygen, and something that greatly aids the process of food digestion and elimination of wastes: fiber.

PROTEINS AND CARBOHYDRATES. Proteins are large molecules built from long chains of amino acids, which are organic compounds made of carbon, hydrogen, oxygen, nitrogen, and (in some cases) sulfur-bonded in characteristic formations. Proteins serve the functions of promoting normal growth, repairing damaged tissue, contributing to the body's immune system, and making enzymes. (An enzyme is a protein material that speeds up chemical reactions in the bodies of plants and animals.) Good examples of dietary proteins include eggs, milk, cheese, and other dairy products. Incomplete proteins, or ones lacking essential amino acids—those amino acids that are not produced by the human body—include peas, beans, lentils, nuts, and cereal grains.

Carbohydrates are compounds that consist of carbon, hydrogen, and oxygen. Their primary function in the body is to supply energy. When a person ingests more carbohydrates than his or her body needs at the moment, the body converts the excess into a compound known as glycogen. It then stores the glycogen in the liver and muscle tissues, where it remains, a potential source of energy for the body to use in the future, though if it is not used soon, it may be stored as fat. The carbohydrate group comprises sugars, starches, cellulose (a type of fiber), and various other chemically related substances.

LIPIDS, VITAMINS, AND MINERALS. Lipids include all fats and oils and are distinguished by the fact that they are soluble (i.e., capable of being dissolved) in oily or fatty substances but not in water. In the body, lipids supply energy much as carbohydrates do, only much more slowly. Lipids also protect the organs from shock and damage and provide the body with insulation from cold, toxins, and other threats. Processed, saturated fats (fats that have been enhanced artificially to make them more

firm) are extremely unhealthy, and consumption of some types of animal fat (e.g., pork fat) is also inadvisable. On the other hand, vegetable fats, such as those in avocados and olive oil, as well as the animal fats in such fish as tuna, mackerel, and salmon can be highly beneficial.

Vitamins are organic substances that, in extremely small quantities, are essential to the nutrition of most animals and some plants. In particular, they work with enzymes in regulating metabolic processes—that is, the chemical processes by which nutrients are broken down and converted into energy or used in the construction of new tissue or other material in the body. Vitamins do not in themselves provide energy, however, and thus they do not qualify as a form of nutrition. Much the same is true of minerals, except that these are inorganic substances, meaning that they do not contain chemical compounds made of carbon and hydrogen.

The Digestive System

To supply the body with the materials it needs for energy and the building of new tissue, nutrients have to pass through the digestive system. The latter is composed of organs (an organ being a group of tissues and cells, organized into a particular structure, that performs a specific function within an organism) and other structures through which nutrients move. The nutrients pass first through the mouth and then through the esophagus, stomach, small intestine, and large intestine, or colon. Collectively, these structures are known as the alimentary canal.

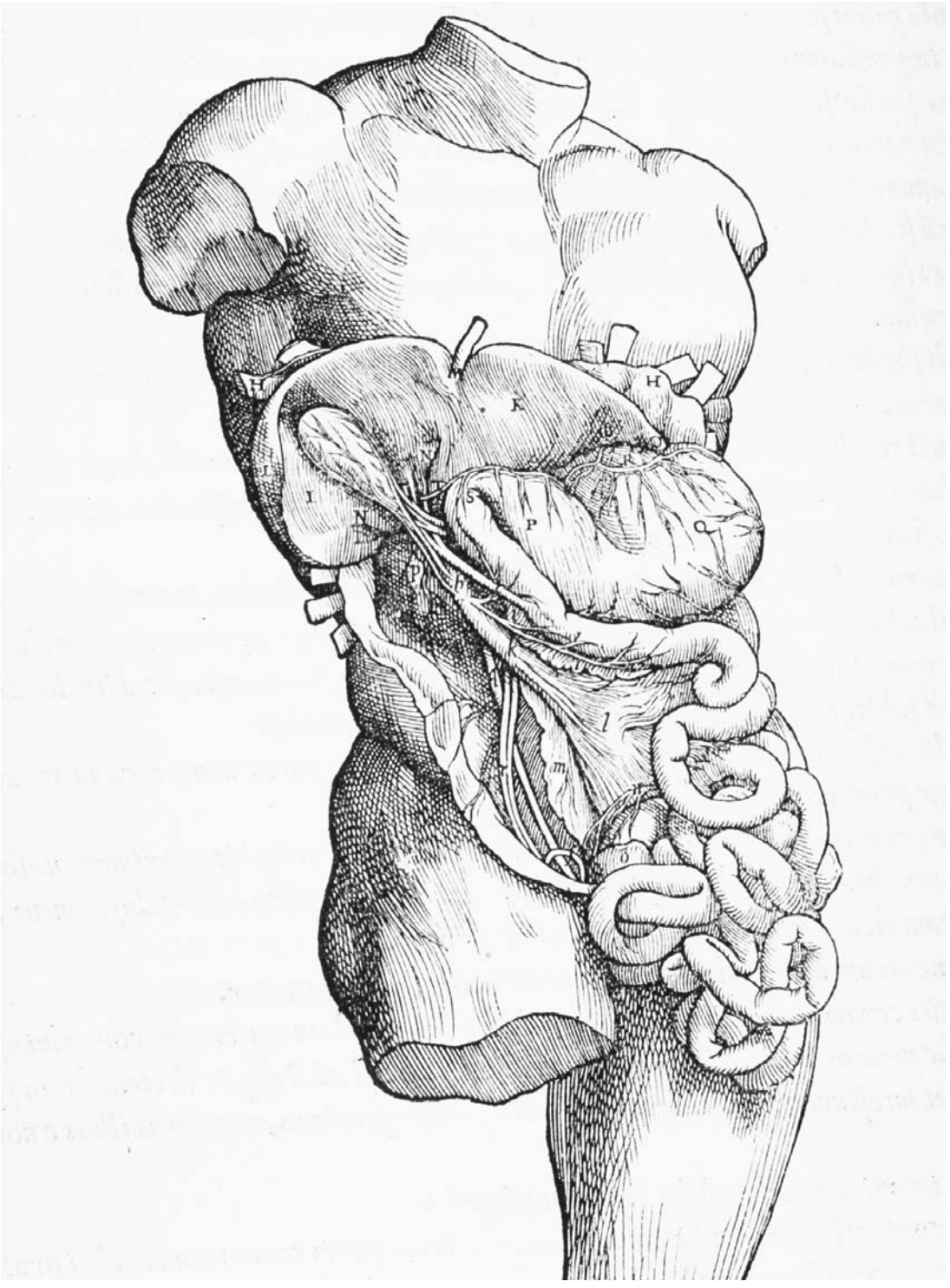
Nutrients advance through the alimentary canal to the stomach and small intestine, and waste materials continue from the small intestine to the colon (large intestine) and anus. Along the way, several glands play a role. A gland is a cell or group of cells that filters material from the blood, processes that material, and secretes it either for use again in the body or to be eliminated as waste. Among the glands that play a part in the digestive process are the salivary glands, liver, gallbladder, and pancreas. (The last three are examples of glands that are also organs.) The glands with a role in digestion secrete digestive juices containing enzymes that break down nutrients chemically into smaller molecules that are absorbed more easily by the body. There are also hormones involved in digestion-there are, for example, glandular cells in the lining of the stomach that make the hormone gastrin.

FROM THE MOUTH TO THE STOMACH. The first stage of digestion is ingestion, in which food is taken into the mouth and then broken down into smaller pieces by the chewing action of the teeth. To facilitate movement of the food through the mouth and along the tongue, it is necessary for saliva to be present. Usually, the sensations of sight, taste, and smell associated with food set in motion a series of neural responses that induce the formation of saliva by the salivary glands in the mouth. Amylase, an enzyme in the saliva, begins the process of breaking complex carbohydrates into simple sugars. (The terms *simple* and *complex* in this context refer to chemical structures.)

By the time it is ready to be swallowed, food is in the form of a soft mass known as a bolus. The action of swallowing pulls the food down through the pharynx, or throat, and into the esophagus, a tube that extends from the bottom of the throat to the top of the stomach. (Note that for the most part, we are using human anatomy as a guide, but many aspects of the digestive process described here also apply to other higher animals, particularly mammals.) The esophagus does not take part in digestion but rather performs the function of moving the bolus into the stomach.

A wavelike muscular motion termed peristalsis, which consists of alternating contractions and relaxations of the smooth muscles lining the esophagus, moves the bolus through this passage. At the place where the esophagus meets the stomach, a powerful muscle called the *esophageal sphincter* acts as a valve to keep food and stomach acids from flowing back into the esophagus and mouth. (Although the most well-known sphincter muscle in the body is the one surrounding the anus, sometimes known simply as "*the* sphincter," in fact, *sphincter* is a general term for a muscle that surrounds, and is able to control the size of, a bodily opening.)

FROM THE STOMACH TO THE SMALL INTESTINE. Chemical digestion begins in the stomach, a large, hollow, pouchlike muscular organ. While food is still in the mouth, the stomach begins its production of gastric juice, which contains hydrochloric acid and pepsin, an enzyme that digests protein. Gastric juice is the material that breaks down the food.



A sixteenth-century anatomical diagram of the internal organs, showing the stomach, liver, intestine, and gallbladder. *(© Corbis. Reproduced by permission.)*

Once nerves in the cheeks and tongue are stimulated by the food, they send messages to the brain, which, in turn, alerts nerves in the stomach wall, stimulating the secretion of gastric juice before the bolus itself arrives in the stomach. Once the bolus touches the stomach lining, it triggers a second release of gastric juice, along with mucus that helps protect the stomach lining from the action of the hydrochloric acid. Three layers of powerful stomach muscles churn food

into a thick liquid called *chyme,* which is pumped gradually through the pyloric sphincter, which connects the stomach small intestine.

THE SMALL INTESTINE. The names of the small and large intestines can be confusing, rather like those of Upper and Lower Egypt in ancient history. In both cases, the adjectives seem to refer to one thing but actually refer to something else entirely. Thus, it so happens that Upper Egypt was south of Lower Egypt (because it was "upper" in elevation, not latitude), while the small intestine is, in fact, much longer than the large intestine. The reason is that *small* refers to its diameter rather than its length: though it is about 23 ft. (7 m) long, the small intestine is only 1 in. (2.5 cm) in diameter, while the large intestine, only 5 ft. (1.5 m) in length, is 3 in. (7.6 cm) across.

The small intestine, which connects the stomach and large intestine, is in three sections: the duodenum, jejunum, and ileum. About 1 ft. (0.3 m) long, the duodenum breaks down chyme from the stomach with the aid of the pancreas and gallbladder. The pancreas, a large gland located below the stomach, secretes pancreatic juice, which contains three enzymes that break down carbohydrates, fats, and proteins, into the duodenum through the pancreatic duct. The gallbladder empties bile, a yellowish or greenish fluid from the liver, into the duodenum when chyme enters that portion of the intestine. Although bile does not contain enzymes, it does have bile salts that help dissolve fats.

Digested carbohydrates, fats, proteins, and most of the vitamins, minerals, and iron in food are absorbed in the jejunum, which is about 4 ft. (1.2 m) long. Aiding this absorption are up to five million tiny finger-like projections called *villi,* which greatly increase the surface area of the small intestine, thus accelerating the rate at which nutrients are absorbed into the bloodstream. The remainder of the small intestine is taken up by the ileum, which is smaller in diameter and has thinner walls than the jejunum. It is the final site for absorption of some vitamins and other nutrients, which enter the circulatory system in plasma, a watery liquid in which red blood cells also are suspended.

As it moves through the circulatory system, plasma takes with it amino acids, enzymes, glycerol (a form of alcohol found in fats), and fatty acids, which it directs to the body's tissues for energy and growth. Plasma also contains waste products from the breakdown of proteins, including creatinine, uric acid, and ammonium salts. These constituents are moved to the kidneys, where they are filtered from the blood and excreted in the urine. But, of course, urine is not the only waste product excreted by the body; there is also the solid waste, processed through the large intestine, or colon.

THE LARGE INTESTINE AND BEYOND. Like the small intestine, the large intestine is in segments. It rises up on the right side of the body (the ascending colon), crosses over to the other side underneath the stomach (the transverse colon), descends on the left side, (the descending colon), and forms an S shape (the sigmoid colon) before reaching the rectum and anus. In addition to its function of pumping solid waste, the large intestine removes water from the waste products—water that, when purified, will be returned to the bloodstream. In addition, millions of bacteria in the large intestine help produce certain B vitamins and vitamin K, which are absorbed into the bloodstream along with the water.

After leaving the sigmoid colon, waste passes through the muscular rectum and then the anus, the last point along the alimentary canal. In all, the movement of food through the entire length of the alimentary tract takes from 15 to 30 hours, with the majority of that time being taken up by activity in the colon. Food generally spends about three to five hours in the stomach, another four to five hours in the small intestine, and between five and 25 hours in the large intestine.

The transit time, or the amount of time it takes for food to move through the system, is a function of diet: for a vegetarian who eats a great deal of fiber, it will be on the short end, while for a meat eater who has just consumed a dinner of prime rib, it will take close to the maximum time. People who eat diets heavy in red meat or junk foods are also likely to experience a buildup, over time, of partially digested material on the linings of their intestines. Obviously, this is not a healthy situation, and to turn it around, a person may have to change his or her diet and perhaps even undergo some sort of colon-cleansing program. There is an easy way to test transit time in one's system: simply eat a large serving of corn or red beets, and measure how long it takes for these to fully work their way through the digestive system.

REAL-LIFE APPLICATIONS

Digestive Disorders

It is hard to watch more than a few minutes of commercial television without seeing advertisements for fast foods and other varieties of junk food or stomach-relief medicine or both. There is a connection, of course: a society glutted on greasy drive-through burgers and thick-crust pizzas needs something to cure the upset stomachs that result.

Indigestion is a general condition that, as its name suggests, involves an inability to digest food properly. Heartburn, sometimes called acid indigestion, is a specific type of indigestion that occurs when the stomach produces too much hydrochloric acid. The latter is essential to digestion, but if a person eats a giant Polish sausage, a spicy-hot bowl of jambalaya, or some other hard-to-digest food (as opposed to a healthy meal of baked fish with brown rice and spinach, for instance), the stomach may produce too much of the acid.

Heartburn is so named because it causes a sharp pain behind the breastbone, which might feel like a heart attack. It also may produce acid reflux, in which the stomach acid backs up into the esophagus. If you have ever experienced what might be called a *leap of vomit,* in which a burp is associated with the rise of burning, foul-tasting bile through the esophagus, then you have first-hand knowledge of acid reflux and heartburn.

Digestive tract diseases, such as dyspepsia, sometimes can cause chronic indigestion, but more often than not, people experience indigestion as a result of eating too quickly or too much, consuming high-fat foods, or eating in a stressful situation. (This is why you might feel sick to your stomach when eating lunch at school on the day of a difficult test, a fight, or a romantic trauma, such as a breakup or asking for a first date.) Smoking, excessive drinking, fatigue, and the consumption of medications that irritate the stomach lining also can contribute to indigestion. In addition, it is a good idea not to eat too soon before going to bed, since this can produce heartburn.

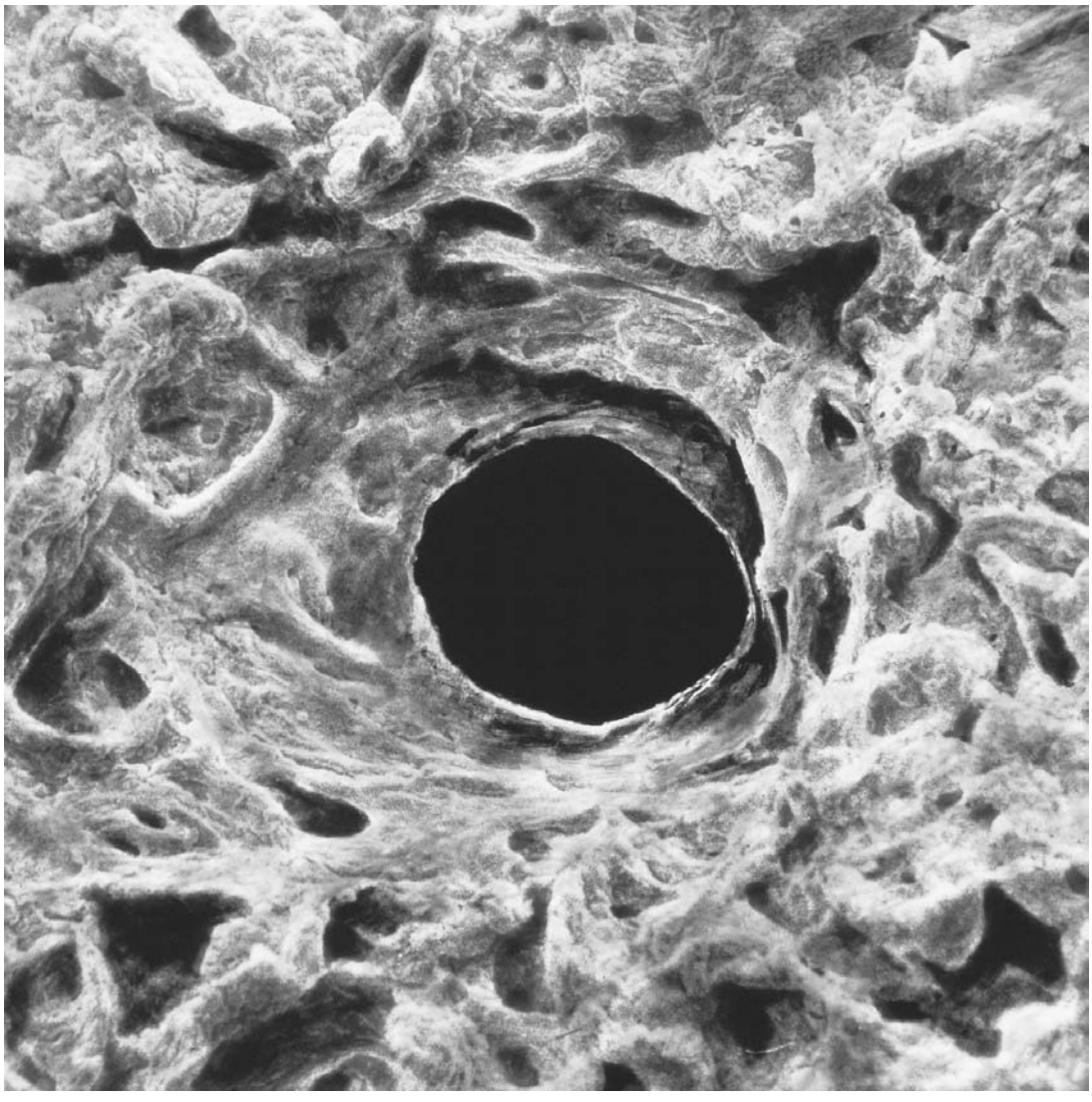
COMMERCIAL ANTACIDS. Most nonprescription stomach-relief medicine is in the form of an antacid, which, as the term suggests, is a substance that works against acids in the stomach. Chemically, the opposite of an acid is a base, or an alkaline substance, the classic example being sodium bicarbonate or sodium hydrogen carbonate ($NaHCO_3$)—that is, baking soda. Baking soda alone can perform the function of an antacid, but the taste is rather unpleasant, and for this reason most antacid products combine it with other chemicals to enhance the flavor.

One famous commercial stomach remedy actually *uses* acid. This is Alka-Seltzer, but the presence of citric acid has more to do with marketing than with the chemistry of the stomach. The citric acid, often used as a sweetener, imparts a more pleasant flavor than the bitter taste of alkaline antacids, and, moreover, when Alka-Seltzer tablets are placed in water, the acid reacts chemically with the sodium bicarbonate to create the product's trademark fizz.

Ultimately, all antacids (Alka-Seltzer included) work because the bases in the product react with the acids in the stomach. This is a chemical process called neutralization, in which the acid and base cancel out each other, producing water and a salt in the process. (Table salt, or sodium chloride, is just one of many salts, all of which are formed by the chemical bonding of a metal with a nonmetal—in the case of table salt, sodium and chlorine, respectively.) Thanks to this process, acid in the stomach of a heartburn sufferer is neutralized.

ULCERS. There are some digestive disorders that cannot be cured by Alka-Seltzer or its many competitors, such as Rolaids, Maalox, Mylanta, Tums, Milk of Magnesia, or Pepto-Bismol. Instead of just occasional indigestion or heartburn, a person may be afflicted with a sore in one part of the digestive tract, which may be either a stomach ulcer or a duodenal ulcer. Stomach ulcers, which form in the lining of the stomach, are called peptic ulcers because they form with the help of stomach acid and pepsin. Duodenal ulcers, which are more common, tend to be smaller than stomach ulcers and heal more quickly. Any ulcer, whether a small sore or a deep cavity, leaves a scar in the alimentary canal.

Until the early 1990s, physicians generally maintained that personal behavior and conditions, such as stress and poor diet, were the principal factors behind ulcer. Medical researchers eventually came to believe, however, that the culprit was a certain bacterium, which can live



Scanning electron micrograph of a stomach ulcer. Instead of just occasional indigestion, a person may be afflicted with an ulcer, or a sore in one part of the digestive tract. Stomach ulcers are called peptic ulcers because they form with the help of stomach acid and pepsin. *(Photo Researchers. Reproduced by permission.)*

undetected in the mucous lining of the stomach. This bacterium irritates and weakens the lining, making it more susceptible to damage by stomach acids. As many as 80% of all stomach ulcers may be caused by such a bacterial infection. With this newfound knowledge, ulcer patients today are more likely to be treated with antibiotics and antacids rather than special diets or expensive medicines.

Ways to Improve Digestion

There are numerous ways to improve digestion, by changing either the way one eats or the things one eats. In the first category, it is important to eat only when you are really hungry and to eat slowly and chew food thoroughly. Drinking liquids with a meal is probably not a good practice; it is better to wait until you are finished, so as not to interfere with the action of digestive fluids. Certainly, smoking and excessive drinking have a negative impact on digestion, whereas regular exercise has a positive influence.

In the category of diet, it is a good idea to minimize one's intake of red meat, such as steak. Although most people find red meat tasty, and it can be a good supplier of dietary iron in limited proportions, the digestion of red meat requires the production of much more stomach acid, and

thus it places a great burden on the digestive system. It is also wise to eliminate as many processed foods as possible, including sweets and junk foods, and to eat as many natural foods as one can manage.

In general, one can hardly go wrong with raw vegetables, which are just about the best thing a person can eat—not only because of their digestive properties but also because many of them are packed so full of vitamins and minerals. (Note that vegetables are best when raw and fresh, since cooking removes many of the nutrients. Canned vegetables usually are both nutrient-poor and full of sodium or even synthetic chemicals. Frozen vegetables are much better than canned ones, but they still do not compare nutritionally with fresh vegetables.)

A good diet includes a great deal of fiber, indigestible material that simply passes through the system, assisting in the peristaltic action of the alimentary canal and in the process of eliminating waste. Cellulose, found in most raw fruits and vegetables, is an example of fiber, also called bulk or roughage. Yogurt may be a beneficial food, because it includes "good" bacteria (a topic we discuss near the conclusion of this essay) that assist the digestive process. Some foods, such as raw bean sprouts, papaya, figs, and pineapple, contain enzymes that appear to assist the body in digesting them.

In addition, one of the greatest "foods" for aiding digestion is not a food at all, but water, of which most people drink far too little. Some experts claim that a person should drink eight 8-oz. (0.24 l) glasses a day, but others maintain that a person should drink half as many ounces of water as his or her weight in pounds. In other words, a person who weighed 100 lb. (45.36 kg) would drink 50 oz. (1.48 l) of water a day, whereas a person who weighed 150 lb. (68.04 kg) would drink 75 oz. (2.22 l). A good rule of thumb for metric users, instead of the 2:1 pounds-to-ounces ratio, would be 30:1 kilograms to liters. Note also that tap water may contain chemicals or other impurities, and therefore consuming it in large quantities is not advisable. A much better alternative is bottled or filtered water.

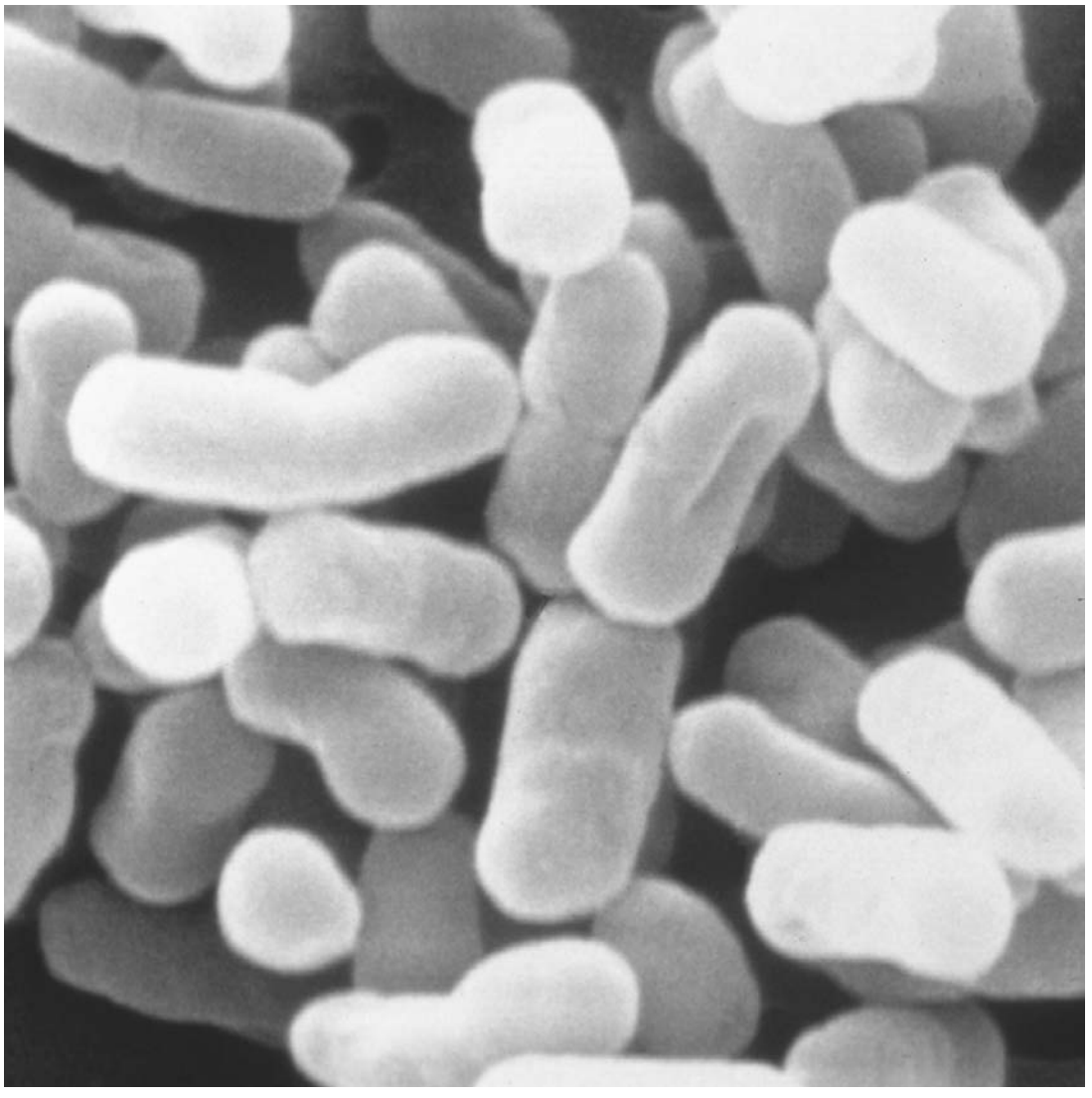
Human Waste

Many years ago, both a serious book and a comedic movie had the title *Everything You Always Wanted to Know about Sex (But Were Afraid to Ask).* Just as the title of David R. Reuben's 1969 book inspired Woody Allen's 1972 movie, which was very loosely based on it, the "Everything you always wanted to know ... " motif inspired a whole array of imitators. Often such titles play on the very fact that hardly anyone wants to know, and certainly no one is afraid to ask, about the topic in question. A good example is an on-line article by central Asia authority Mark Dickens entitled "Everything You Always Wanted to Know about Tocharian But Were Afraid To Ask" (http://www.oxuscom.com/eyawtkat.htm). The joke, of course, is that most people have never heard of Tocharian, a central Asian language. Nonetheless, one subject ranks with sex as something everyone wonders about but most are afraid to ask.

Even the name of that topic creates problems, since people have so many euphemisms for it: "number two," for instance, or BM (short for bowel movement). There are baby- and child-oriented terms for this process and product, the bodily control of which can be a major problem for a very young human being, and, of course, there is at least one grown-up term for it that will not be mentioned here. People even have nicknames for animal dung, such as pies, patties, or chips. For the sake of convenience, let us call the process defecation, and the product human waste (or excrement or feces) and admit that everyone has wondered how something as pleasant as food can, after passing through the alimentary canal, turn into something as unpleasant as the final product.

The average person excretes some 7 lb. (3.2 kg) of feces per day, an amount equal to a little more than 1 ton (0.91 tonnes) per year. This waste is made up primarily of indigestible materials as well as water, salts, mucus, cellular debris from the intestines, bacteria, and cellulose and other types of fiber. Like the human body itself, these waste products are mostly water: about 75%, compared with 25% solid matter. Much of what goes into producing excrement has nothing to do with what enters the digestive system, so even if a person were starving he or she would continue to excrete feces.

Coloration. What about the color and the smell? The color of feces comes from



ESCHERICHIA COLI IS A TYPE OF BACTERIA THAT LIVES IN THE INTESTINAL TRACT, AIDING THE DIGESTIVE PROCESS BY SUPPRESSING THE GROWTH OF HARMFUL BACTERIA AND SYNTHESIZING VITAMINS. *(© 1997 Custom Medical Stock Photo. Reproduced by permission.)*

bilirubin, a reddish-yellow pigment found in blood and bile, which passes through the liver and enters the small intestine via the gallbladder. Later, as it passes through the large intestine, it is degraded by the action of bacteria, a process that turns it brown and gives feces its characteristic color.

Not surprisingly, disorders involving the red blood cells, liver, or gallbladder can change the color of human waste. A person with gallstones or hepatitis (a disease characterized by inflammation of the liver) is likely to excrete grayish-brown feces, while anemia (a condition that involves a lack of red blood cells) may be associated with a yellowish stool. A person experiencing bleeding in the gastrointestinal tract (the stomach and intestines) may produce waste the color of black tar. In addition, foods with distinctive colors and textures also can affect the appearance of stools.

FRIENDLY BACTERIA. Before addressing the smell of feces, which is the result of action by bacteria in the colon, it is worth saying a few words about those single-cell organisms themselves. This is especially important in light of the fact that bacteria have a bad reputation that is not entirely deserved. Without question, there are harmful microbes in the world, but a world completely free of these organisms

KEY TERMS

ALIMENTARY CANAL: The entire length of tube that extends from the mouth to the anus, including the esophagus, stomach, and small and large intestines. Nutrients pass through the alimentary canal to the stomach and small intestine, and waste materials from these nutrients (and from other sites in the body) pass from the small intestine to the colon (large intestine) and anus.

AMINO ACIDS: Organic compounds made of carbon, hydrogen, oxygen, nitrogen, and (in some cases) sulfur bonded in characteristic formations. Strings of amino acids make up proteins.

BILE: A yellowish or greenish digestive fluid excreted by the liver.

BOLUS: A term for a chewed mass of food making its way through the initial portions of the alimentary canal.

CARBOHYDRATES: Naturally occurring compounds, consisting of carbon, hydrogen, and oxygen, whose primary function in the body is to supply energy. Included in the carbohydrate group are sugars, starches, cellulose, and various other substances.

CELLULOSE: A polysaccharide that is the principal material in the cell walls of plants. Cellulose also is found in such natural fibers as cotton and is used as a raw material in manufacturing such products as paper.

COLON: The large intestine, through which waste materials pass on their way to excretion through the anus.

COMPOUND: A substance in which atoms of more than one element are bonded chemically to one another.

ENZYME: A protein material that speeds up chemical reactions in the bodies of plants and animals.

FIBER: Indigestible material in food that simply passes through the digestive system, assisting in the peristaltic action of the alimentary canal and in the processing of waste. Examples of fiber, also called *bulk* or *roughage,* include cellulose.

GASTROINTESTINAL TRACT: The stomach and intestines.

GLAND: A cell or group of cells that filters material from the blood, processes that material, and secretes it either for use again in the body or to be eliminated as waste.

GLUCOSE: A type of sugar that occurs widely in nature. Glucose is the form in which animals usually receive carbohydrates.

GLYCOGEN: A white polysaccharide that is the most common form in which carbohydrates are stored in animal tissues, particularly muscle and liver tissues.

GUT: A term that refers to all or part of the alimentary canal. Although the word is considered a bit crude in everyday life, physicians and biological scientists concerned with this part of the anatomy use it regularly.

would be one in which humans and other animals would be unable to live. In fact, we have a mutually beneficial relationship, a type of symbiosis (see Symbiosis) with the microorganisms in our alimentary canals, particularly in the colon.

Bacteria live in the guts—a term that refers to all or part of the alimentary canal—of most ani-

KEY TERMS CONTINUED

HEMOGLOBIN: An iron-containing pigment in red blood cells that is responsible for transporting oxygen to the tissues and removing carbon dioxide from them.

LIPIDS: Fats and oils, which dissolve in oily or fatty substances but not in water-based liquids. In the body, lipids supply energy in slow-release doses, protect organs from shock and damage, and provide insulation for the body, for instance, from toxins.

METABOLISM: The chemical process by which nutrients are broken down and converted into energy or used in the construction of new tissue or other material in the body.

MINERALS: Inorganic substances that, in a nutritional context, serve a function similar to that of vitamins. Minerals may include chemical elements, particularly metallic ones, such as calcium or iron, as well as some compounds.

ORGAN: A group of tissues and cells, organized into a particular structure, that performs a specific function within an organism.

ORGANIC: At one time, chemists used the term *organic* only in reference to living things. Now the word is applied to compounds containing carbon and hydrogen.

PERISTALSIS: A series of involuntary muscle contractions that force bolus, and later waste, through the alimentary canal.

POLYSACCHARIDE: A complex sugar, in which the molecules are composed of many glucose subunits arranged in a chain. Polysaccharides can be broken down chemically to produce simple sugars, or monosaccharides.

PROTEINS: Large molecules built from long chains of amino acids. Proteins serve the functions of promoting normal growth, repairing damaged tissue, contributing to the body's immune system, and making enzymes.

SPHINCTER: A general term for a muscle that surrounds and is able to control the size of a bodily opening.

SYMBIOSIS: A biological relationship in which (usually) two species live in close proximity to each other and interact regularly in such a way as to benefit one or both of the organisms.

TISSUE: A group of cells, along with the substances that join them, that forms part of the structural materials in plants or animals.

VITAMINS: Organic substances that, in extremely small quantities, are essential to the nutrition of most animals and some plants. In particular, vitamins work with enzymes in regulating metabolic processes; they do not in themselves provide energy, however, and thus vitamins alone do not qualify as a form of nutrition.

mals, where they assist in such difficult digestive activities as the processing of chewed grasses. The latter is heavy in cellulose, and to digest it, cows, sheep, deer, and other grass eaters (known as ruminants) have stomachs with several compartments. The first of these compartments is called the rumen, and it serves as home to millions of bacteria, which assist in breaking down the heavy fibers.

Humans' bacterial symbiotic partners (actually, this is a type of symbiosis known as mutualism, in which both creatures benefit) include bacteria of the species *Escherichia coli,* or *E. coli.* The name is no doubt familiar to most readers from its appearance in the news in connection with horror stories involving *E. coli* poisoning in food or local water supplies. Certainly, *E. coli* can be extremely harmful when it is outside the human gut, but inside the gut it is humans' friend.

E. coli is a coprophile (literally, "excrement lover"), meaning that it depends on feces for survival. Fecal matter itself can contain all manner of harmful substances associated with the decomposition of foods or with the body's efforts to rid itself of toxins (including pathogens, or disease-carrying parasites—see Parasites and Parasitology), so anything associated with feces is dirty and potentially dangerous. It is for this reason that *E. coli* can cause serious illness or death if it gets into other parts of the body.

As long as it stays where it belongs, however, *E. coli* not only aids in the digestive process but also provides the body with vitamin K, essential for proper blood clotting, as well as vitamin B_{12}, thiamine, and riboflavin. Every person carries millions and millions of these helpful fellow travelers; even though a single bacterium weighs almost nothing in human terms, the combined weight of all the helpful, "good" bacteria in our guts is a staggering 7 lb. (3.2 kg).

INTESTINAL GAS. As those bacteria do their work, they generate vast quantities of gases, which are by-products of the chemical processes that play a part in breaking down the foods passing through the gut. Among these gaseous products are hydrogen sulfide, a foul-smelling substance that can be toxic in large quantities. Unlike carbon monoxide, which has no odor, few people are in danger of dying from inhalation of hydrogen sulfide—even though it is abundant in nature—because the smell is enough to dissuade anyone from inhaling it for long periods of time. (Incidentally, gas companies include traces of hydrogen sulfide with natural gas. By itself, natural gas is odorless, but when a leak occurs, a homeowner will smell hydrogen sulfide and alert the gas company.)

Hydrogen sulfide is just one of many unpleasant-smelling chemical products that result from bacterial action on solids in the gut. Others include indole, skatole, ammonia, and mercaptans, though the most distinctive-smelling of all are indole and skatole, which come primarily from the digestion of an amino acid known as tryptophan. In addition, the particular foods a person eats, as well as the specific bacterial residents (some harmful) of his or her gut, can affect the odor of intestinal gas.

When gases pass outside the rectum, the result is flatulence (of course, there are other, less polite words for it), which is the subject of much schoolboy humor. Even inside the body, intestinal gas can make noise and cause embarrassment, in the form of borborygmus—intestinal rumbling caused by moving gas. As for the flammability of intestinal gas, it probably results from the high proportion of hydrogen, an extremely flammable gas.

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RESPIRATION

CONCEPT

Respiration is much more than just breathing; in fact, the term refers to two separate processes, only one of which is the intake and outflow of breath. At least cellular respiration, the process by which organisms convert food into chemical energy, requires oxygen; on the other hand, some forms of respiration are anaerobic, meaning that they require no oxygen. Such is the case, for instance, with some bacteria, such as those that convert ethyl alcohol to vinegar. Likewise, an anaerobic process can take place in human muscle tissue, producing lactic acid—something so painful that it feels as though vinegar itself were being poured on an open sore.

HOW IT WORKS

Forms of Respiration

Respiration can be defined as the process by which an organism takes in oxygen and releases carbon dioxide, one in which the circulating medium of the organism (e.g., the blood) comes into contact with air or dissolved gases. Either way, this means more or less the same thing as breathing. In some cases, this meaning of the term is extended to the transfer of oxygen from the lungs to the bloodstream and, eventually, into cells or the release of carbon dioxide from cells into the bloodstream and thence to the lungs, from whence it is expelled to the environment. Sometimes a distinction is made between external respiration, or an exchange of gases with the external environment, and internal respiration, an exchange of gases between the body's cells and the blood, in which the blood itself "bathes" the cells with oxygen and receives carbon dioxide to transfer to the environment.

This is just one meaning—albeit a more familiar one—of the word respiration. Respiration also can mean cellular respiration, a series of chemical reactions within cells whereby food is "burned" in the presence of oxygen and converted into carbon dioxide and water. This type of respiration is the reverse of photosynthesis, the process by which plants convert dioxide and water, with the aid of solar energy, into complex organic compounds known as carbohydrates. (For more about carbohydrates and photosynthesis, see Carbohydrates.)

How Gases Move Through the Body

Later in this essay, we discuss some of the ways in which various life-forms breathe, but suffice it to say for the moment—hardly a surprising revelation!—that the human lungs and respiratory system are among the more complex mechanisms for breathing in the animal world. In humans and other animals with relatively complex breathing mechanisms (i.e., lungs or gills), oxygen passes through the breathing apparatus, is absorbed by the bloodstream, and then is converted into an unstable chemical compound (i.e., one that is broken down easily) and carried to cells. When the compound reaches a cell, it is broken down and releases its oxygen, which passes into the cell.

On the "return trip"—that is, the reverse process, which we experience as exhalation—cells release carbon dioxide into the bloodstream, where it is used to form another unstable chemical compound. This compound is carried by the

bloodstream back to the gills or lungs, and, at the end of the journey, it breaks down and releases the carbon dioxide to the surrounding environment. Clearly, the one process is a mirror image of the other, with the principal difference being the fact that oxygen is the key chemical component in the intake process, while carbon dioxide plays the same role in the process of outflow.

Hemoglobin and other compounds. In humans the compound used to transport oxygen is known by the name hemoglobin. Hemoglobin is an iron-containing protein in red blood cells that is responsible for transporting oxygen to the tissues and removing carbon dioxide from them. In the lungs, hemoglobin, known for its deep red color, reacts with oxygen to form oxyhemoglobin. Oxyhemoglobin travels through the bloodstream to cells, where it breaks down to form hemoglobin and oxygen, and the oxygen then passes into cells. On the return trip, hemoglobin combines with carbon dioxide to form carbaminohemoglobin, an unstable compound that, once again, breaks down—only this time it is carbon dioxide that it releases, in this case to the surrounding environment rather than to the cells.

In other species, compounds other than hemoglobin perform a similar function. For example, some types of annelids, or segmented worms, carry a green blood protein called chlorocruorin that functions in the same way as hemoglobin does in humans. And whereas hemoglobin is a molecule with an iron atom at the center, the blood of lobsters and other large crustaceans contains hemocyanin, in which copper occupies the central position. Whatever the substance, the compound it forms with oxygen and carbon dioxide must be unstable, so that it can break down easily to release oxygen to the cells or carbon dioxide to the environment.

Cellular Respiration

Both forms of respiration involve oxygen, but cellular respiration also involves a type of nutrient—materials that supply energy, or the materials for forming new tissue. Among the key nutrients are carbohydrates, naturally occurring compounds that consist of carbon, hydrogen, and oxygen. Included in the carbohydrate group are sugars, starches, cellulose, and various other substances.

Glucose is a simple sugar produced in cells by the breakdown of more complex carbohydrates, including starch, cellulose, and such complex sugars as sucrose (cane or beet sugar) and fructose (fruit sugar). In cellular respiration, an organism oxidizes glucose (i.e., combines it with oxygen) so as to form the energy-rich compound known as adenosine triphosphate (ATP). ATP, critical to metabolism (the breakdown of nutrients to provide energy or form new material), is the compound used by cells to carry out most of their ordinary functions. Among those functions are the production of new cell parts and chemicals, the movement of compounds through cells and the body as a whole, and growth.

In cellular respiration, six molecules of glucose ($C_6H_{12}O_6$) react with six molecules of oxygen (O_2) to form six molecules of carbon dioxide (CO_2), six molecules of water (H_2O), and 36 molecules of ATP. This can be represented by the following chemical equation:

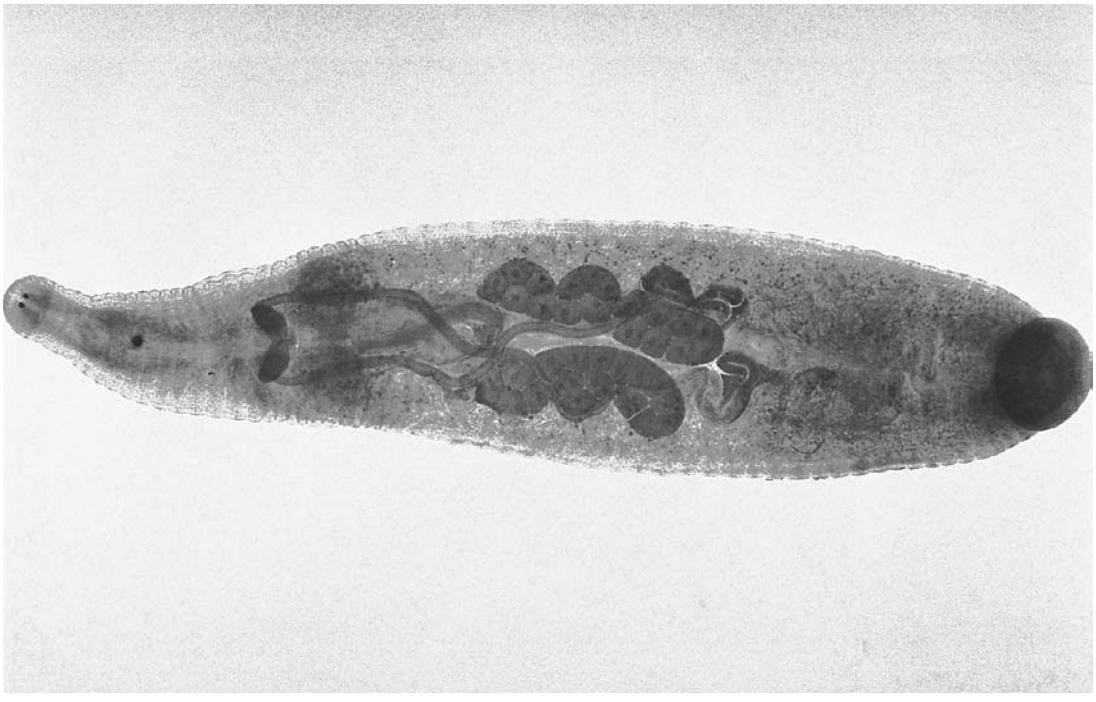
$$6C_6H_{12}O_6 + 6\ O_2 \rightarrow \quad 6\ CO_2 + 6\ H_2O + 36\ ATP$$

The process is much more complicated than this equation makes it appear: some two dozen separate chemical reactions are involved in the overall conversion of glucose to carbon dioxide, water, and ATP.

The Mechanics of Breathing

All animals have some mechanism for removing oxygen from the air and transmitting it into the bloodstream, and this same mechanism typically is used to expel carbon dioxide from the bloodstream into the surrounding environment. Types of animal respiration, in order of complexity, include direct diffusion, diffusion into blood, tracheal respiration, respiration with gills, and finally, respiration through lungs. Microbes, fungi, and plants all obtain the oxygen they use for cellular respiration directly from the environment, meaning that there are no intermediate organs or bodily chemicals, such as lungs or blood. More complex organisms, such as sponges, jellyfish, and terrestrial (land) flatworms, all of which have blood, also breathe through direct diffusion. The latter term describes an exchange of oxygen and carbon dioxide directly between an organism, or its bloodstream, and the surrounding environment.

More complex is the method of diffusion into blood whereby oxygen passes through a moist layer of cells on the body surface and then



ONE FORM OF RESPIRATION IS DIFFUSION INTO BLOOD, WHEREBY OXYGEN PASSES THROUGH A MOIST LAYER OF CELLS ON THE BODY SURFACE, THEN THROUGH CAPILLARY WALLS AND INTO THE BLOODSTREAM, WHERE IT MOVES ON TO TISSUES AND CELLS. AMONG THE ORGANISMS THAT RELY ON DIFFUSION INTO BLOOD ARE ANNELIDS, A GROUP THAT INCLUDES LEECHES. *(© Lester V. Bergman/Corbis. Reproduced by permission.)*

through capillary walls (capillaries are small blood vessels that form a network throughout the body) and into the bloodstream. Once oxygen is in the blood, it moves throughout the body to different tissues and cells. Among the organisms that rely on diffusion into blood are annelids, a group that includes earthworms, various marine worms, and leeches.

In tracheal respiration air moves through openings in the body surface called spiracles. It then passes into special breathing tubes called tracheae that extend into the body. The tracheae divide into many small branches that are in contact with muscles and organs. In small insects, air simply moves into the tracheae, while in large insects, body movements assist tracheal air movement. Insects and terrestrial arthropods (land-based organisms with external skeletons) use this method of respiration.

Much more complicated than tracheae, gills are specialized tissues with many infoldings. Each gill is covered by a thin layer of cells and filled with blood capillaries. These capillaries take up oxygen dissolved in water and expel carbon dioxide dissolved in blood. Fish and other aquatic animals use gills, as did the early ancestors of humans and other higher animals. A remnant of this chapter from humans' evolutionary history can be seen in the way that an embryo breathes in its mother's womb, not by drawing in oxygen through its lungs but through gill-like mechanisms that disappear as the embryo develops.

LUNGS. Lungs are composed of many small chambers or air sacs surrounded by blood capillaries. Thus, they work with the circulatory system, which transports oxygen from inhaled air to all tissues of the body and also transports carbon dioxide from body cells to the lungs to be exhaled. After air enters the lungs, oxygen moves into the bloodstream through the walls of these capillaries. It then passes from the lung capillaries to the different muscles and organs of the body.

Although they are common to amphibians, reptiles, birds, and mammals, lungs differ enormously throughout the animal kingdom. Frogs, for instance, have balloon-like lungs that do not have a very large surface area. By contrast, if the entire surface of an adult male human's lungs were spread flat, it would cover about 750 sq. ft. (70 m^2), approximately the size of a handball court. The reason is that humans have about 300

million gas-filled alveoli, tiny protrusions inside the lungs that greatly expand the surface area for gas exchange.

Birds have specialized lungs that use a mechanism called crosscurrent exchange, which allows air to flow in one direction only, making for more efficient oxygen exchange. They have some eight thin-walled air sacs attached to their lungs, and when they inhale, air passes through a tube called the bronchus and enters posterior air sacs—that is, sacs located toward the rear. At the same time, air in the lungs moves forward to anterior air sacs, or ones located near the bird's front. When the bird exhales, air from the rear air sacs moves to the outside environment, while air from the front moves into the lungs. This efficient system moves air forward through the lungs when the bird inhales and exhales and makes it possible for birds to fly at high altitudes, where the air has a low oxygen content.

Humans and other mammals have lungs in which air moves in and out through the same pathway. This is true even of dolphins and whales, though they differ from humans in that they do not take in nutrition through the same opening. In fact, terrestrial mammals, such as the human, horse, or dog, are some of the only creatures that possess two large respiratory openings: one purely for breathing and smelling and the other for the intake of nutrients as well as air (i.e., oxygen in and carbon dioxide out).

REAL-LIFE APPLICATIONS

Anaerobic Respiration

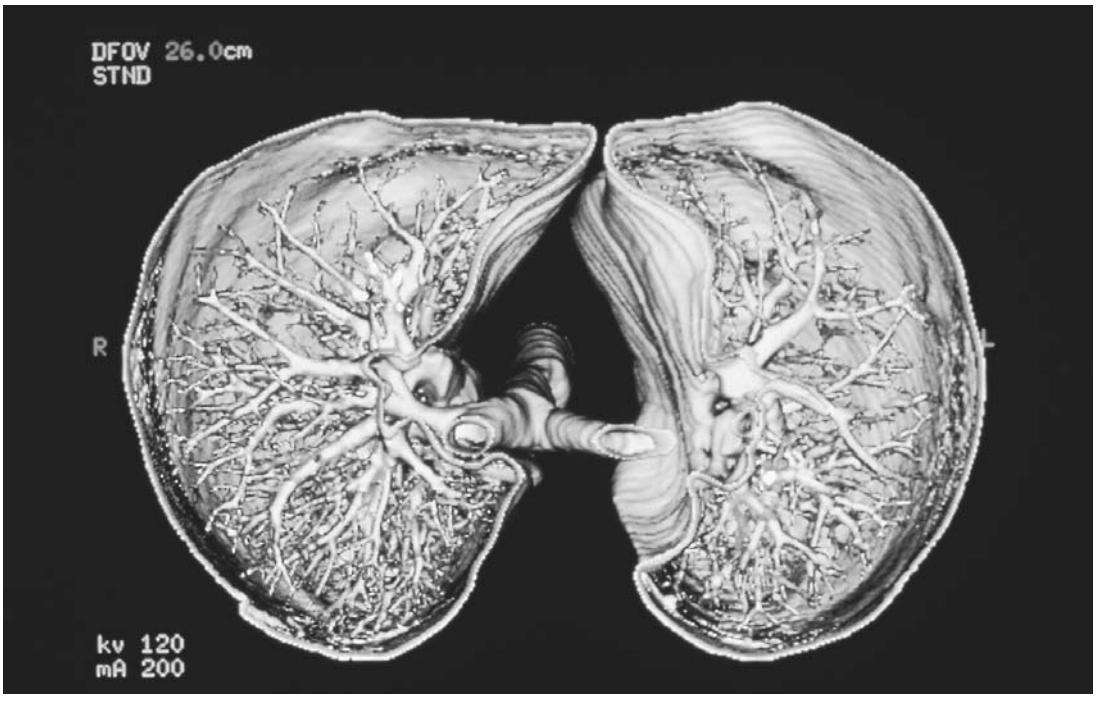
Activity that involves oxygen is called aerobic; hence the term aerobic exercise, which refers to running, calisthenics, biking, or any other form of activity that increases the heart rate and breathing. Activity that does not involve oxygen intake is called anaerobic. Weightlifting, for instance, will increase the heart rate and rate of breathing if it is done intensely, but that is not its purpose and it does not depend on the intake and outflow of breath. For that reason, it is called an anaerobic exercise—though, obviously, a person has to keep breathing while doing it.

In fact, a person cannot consciously stop breathing for a prolonged period, and for this reason, people cannot kill themselves simply by holding their breath. A buildup of carbon dioxide and hydrogen ions (electrically charged atoms) in the bloodstream stimulates the breathing centers to become active, no matter what we try to do. On the other hand, if a person were underwater, the lungs would draw in water instead of air, and though water contains air, the drowning person would suffocate.

ANAEROBIC BACTERIA. Some creatures, however, do not need to breathe air but instead survive by anaerobic respiration. This is true primarily of some forms of bacteria, and indeed scientists believe that the first organisms to appear on Earth's surface were anaerobic. Those organisms arose when Earth's atmosphere contained very little oxygen, and as the composition of the atmosphere began to incorporate more oxygen over the course of many millions of years, new organisms evolved that were adapted to that condition.

The essay on paleontology discusses Earth's early history, including the existence of anaerobic life before the formation of oxygen in the atmosphere. The appearance of oxygen is a result of plant life, which produces it as a by-product of the conversion of carbon dioxide that takes place in photosynthesis. Plants, therefore, are technically anaerobic life-forms, though that term usually refers to types of bacteria that neither inhale nor exhale oxygen. Anaerobic bacteria still exist on Earth and serve humans in many ways. Some play a part in the production of foods, as in the process of fermentation. Other anaerobic bacteria have a role in the treatment of sewage. Living in an environment that would kill most creatures—and not just because of the lack of oxygen—they consume waste materials, breaking them down chemically into simpler compounds.

HUMANS AND ANAEROBIC RESPIRATION. Even in creatures, such as humans, that depend on aerobic respiration, anaerobic respiration can take place. Most cells are able to switch from aerobic to anaerobic respiration when necessary, but they generally are not able to continue producing energy by this process for very long. For example, a person who exercises vigorously may be burning up glucose faster than oxygen is being pumped to the cells, meaning that cellular respiration cannot take place quickly enough to supply all the energy the body needs. In that case, cells switch over to



Computerized tomographic view of the lungs, showing the trachea (center) splitting to form the two main bronchi, which lead to the lungs. Inside the lungs, many branching bronchi terminate in alveoli, air sacs where gas exchange takes place. *(© BSIP/Gems Europe/Photo Researchers. Reproduced by permission.)*

anaerobic respiration, which results in the production of lactic acid, or $C_3H_6O_3$. One advantage of anaerobic respiration is that it can take place very quickly and in short bursts, as opposed to aerobic respiration, which is designed for slower and steadier use of muscles. The disadvantage is that anaerobic respiration produces lactic acid, which, when it builds up in muscles that are overworked, causes soreness and may even lead to cramps.

Lactic acid in the body. Eventually, the buildup of lactic acid is carried away in the bloodstream, and the lactic acid is converted to carbon dioxide and water vapor, both of which are exhaled. But if lactic acid levels in the bloodstream rise faster than the body can neutralize them, a state known as lactic acidosis may ensue. Lactic acidosis rarely happens in healthy people and, more often than not, is a result of the body's inability to obtain sufficient oxygen, as occurs in heart attacks or carbon monoxide or cyanide poisoning or in the context of diseases such as diabetes.

The ability of the body to metabolize lactic acid is diminished significantly by alcohol, which impairs the liver's ability to carry out normal metabolic reactions. For this reason, alcoholics often have sore muscles from lactic acid buildup, even though they may not exercise. Lactic acid also can lead to a buildup of uric acid crystals in the joints, in turn causing gout, a very painful disease.

Lactic acid in food and industry. Lactic acid is certainly not without its uses, and it is found throughout nature. When lactose, or milk sugar, is fermented by the action of certain bacteria, it causes milk to sour. The same process is used in the manufacture of yogurt, but the reaction is controlled carefully to ensure the production of a consumable product. Lactic acid also is applied by the dairy industry in making cheese. Molasses contains lactic acid, a product of the digestion of sugars by various species of bacteria, and lactic acid also is used in making pickles and sauerkraut, foods for which a sour taste is desired.

A compound made from lactic acid is used as a food preservative, but the applications of lactic acid extend far beyond food production. Lactic acid is important as a starting material for making drugs in the pharmaceutical industry. Additionally, it is involved in the manufacturing of lacquers and inks; is used as a humectant, or moisturizer, in some cosmetics; is applied as a

mordant, or a chemical that helps fabrics accept dyes, to textiles; and is employed in tanning leather.

Respiratory Disorders

In almost any bodily system, there are bound to be disorders, or at least the chance that disorders may occur. This is particularly the case with something as complex as the respiratory system, because the more complex the system, the more things that can go wrong. Among the respiratory disorders that affect humans is a whole range of ailments from the common cold to emphysema, and from the flu to cystic fibrosis.

THE COMMON COLD. Colds are among the most common conditions that affect the respiratory system, though what we call the common cold is actually an invasion by one of some 200 different types of virus. Thus, it is really not one ailment but 200, though these are virtually identical, but the large number of viral causative agents has made curing the cold an insurmountable task.

When you get a cold, viruses establish themselves on the mucus membrane that coats the respiratory passages that bring air to your lungs. If your immune system is unsuccessful in warding off this viral infection, the nasal passages become inflamed, swollen, and congested, making it difficult to breathe.

Coughing is a reflex action whereby the body attempts to expel infected mucus or phlegm. It is essential to removing infected secretions from the body, but of course it plays no role in actually bringing a cold to an end. Nor do antibiotics, which are effective against bacteria but not viruses (see Infection). Only when the body builds up its own defense to the cold—assuming the sufferer has a normally functioning immune system—is the infection driven away.

INFLUENZA AND ALLERGIES. Influenza, a group of viral infections that can include swine flu, Asian flu, Hong Kong flu, and Victoria flu, is often far more serious than the common cold. A disease of the lungs, it is highly contagious, and can bring about fever, chills, weakness, and aches. In addition, influenza can be fatal: a flu epidemic in the aftermath of World War I, spread to far corners of the globe by returning soldiers, killed an estimated 20 million people.

Respiratory ailments often take the form of allergies such as hay fever, symptoms of which include sneezing, runny nose, swollen nasal tissue, headaches, blocked sinuses, fever, and watery, irritated eyes. Hay fever is usually aggravated by the presence of pollen or ragweed in the air, as is common in the springtime. Other allergy-related respiratory conditions may be aggravated by dust in the air, and particularly by the feces of dust mites that live on dust particles.

BRONCHIAL AILMENTS. Allergic reactions can be treated by antihistamines (see The Immune System for more about allergies), but simple treatments are not available for such complex respiratory disorders as asthma, chronic bronchitis, and emphysema. All three are characterized by an involuntary constriction in the walls of the bronchial tubes (the two divisions of the trachea or windpipe that lead to the right and left lungs), which causes the tubes to close in such a way that it becomes difficult to breathe.

Emphysema can be brought on by cigarette smoking, and indeed some heavy smokers die from that ailment rather than from lung cancer. On the other hand, a person can contract a bronchial illness without engaging in smoking or any other activity for which the sufferer could ultimately be blamed. Indeed, small children may have asthma. One treatment for such disorders is the use of a bronchodilator, a medicine used to relax the muscles of the bronchial tubes. This may be administered as a mist through an inhaler, or given orally like other medicine.

TUBERCULOSIS AND PNEUMONIA. More severe is tuberculosis, an infectious disease of the lungs caused by bacteria. Tuberculosis attacks the lungs, leading to a chronic infection with such symptoms as fatigue, loss of weight, night fevers and chills, and persistent coughing that brings up blood. Without treatment, it is likely to be fatal. Indeed, it was a significant cause of death until the introduction of antibiotics in the 1940s, and it has remained a problem in underdeveloped nations. Additionally, thanks to mutation in the bacteria themselves, strains of the disease are emerging that are highly resistant to antibiotics.

Another life-threatening respiratory disease is pneumonia, an infection or inflammation of the lungs caused by bacteria, viruses, mycoplasma (microorganisms that show similarities to

KEY TERMS

AEROBIC: Oxygen-breathing.

ANAEROBIC: Non-oxygen-breathing.

ATP: Adenosine triphosphate, an energy carrier formed when a simpler compound, adenosine diphosphate (ADP), combines with a phosphate group.

CAPILLARY: A very small blood vessel. Capillaries form networks throughout the body.

CARBOHYDRATES: Naturally occurring compounds, consisting of carbon, hydrogen, and oxygen, whose primary function in the body is to supply energy. Included in the carbohydrate group are sugars, starches, cellulose, and various other substances. Most carbohydrates are produced by green plants in the process of undergoing photosynthesis.

CELLULAR RESPIRATION: A process that, when it takes place in the presence of oxygen, involves the intake of organic substances, which are broken down into carbon dioxide and water, with the release of considerable energy.

CIRCULATORY SYSTEM: The parts of the body that work together to move blood and lymph. They include the heart, blood vessels, blood, and the lymphatic glands, such as the lymph nodes.

COMPOUND: A substance in which atoms of more than one element are bonded chemically to one another.

FERMENTATION: A process, involving enzymes, in which a compound rich in energy is broken down into simpler substances.

GLUCOSE: A monosaccharide (sugar) that occurs widely in nature and which is the form in which animals usually receive carbohydrates. Also known as *dextrose, grape sugar,* and *corn sugar.*

HEMOGLOBIN: An iron-containing protein in human red blood cells that is responsible for transporting oxygen to the tissues and removing carbon dioxide from them. Hemoglobin is known for its deep red color.

LYMPH: The portion of the blood that includes white blood cells and plasma but not red blood cells.

LYMPH NODES: Masses of tissue, at certain places in the body, that act as filters for blood.

METABOLISM: The chemical process by which nutrients are broken down and converted into energy or are used in the construction of new tissue or other material in the body. All metabolic reactions are either catabolic or anabolic.

MONOSACCHARIDE: The simplest type of carbohydrate. Monosaccharides, which cannot be broken down chemically into simpler carbohydrates, also are known as *simple sugars.*

NUTRIENT: Materials that supply energy or the materials to form new tissue for organisms. They include proteins, carbohydrates, lipids (fats), vitamins, and minerals.

PHOSPHATE GROUP: A group (that is, a combination of atoms from two or more elements that tend to bond with other elements or compounds in certain characteristic ways) involving a phosphate, or a chemical compound that contains oxygen bonded to phosphorus.

KEY TERMS CONTINUED

PHOTOSYNTHESIS: The biological conversion of light energy (that is, electromagnetic energy) from the Sun to chemical energy in plants. In this process carbon dioxide and water are converted to carbohydrates and oxygen.

RESPIRATION: A term that can refer either to cellular respiration (see definition) or, more commonly, to the process by which an organism takes in oxygen and releases carbon dioxide. Sometimes a distinction is made between external respiration, or an exchange of gases with the external environment, and internal respiration, an exchange of gases between the body's cells and the blood.

SIMPLE SUGAR: A monosaccharide, or simple carbohydrate.

TISSUE: A group of cells, along with the substances that join them, that forms part of the structural materials in plants or animals.

both viruses and bacteria), and fungi, as well as such inorganic agents as inhaled dust or gases. Symptoms include pleurisy (chest pain), high fever, chills, severe coughing that brings up small amounts of mucus, sweating, blood in the sputum (saliva and mucus expelled from the lungs), and labored breathing.

In 1936, pneumonia was the principal cause of death in the United States. Since then, it has been controlled by antibiotics, but as with tuberculosis, resistant strains of bacteria have developed, and therefore the number of cases has increased. Today, pneumonia and influenza combined are among the most significant causes of death in the United States (see Diseases).

LUNG CANCER AND CYSTIC FIBROSIS. Respiratory ailments may also take the form of lung cancer, which may or may not be a result of smoking. Cigarette smoking and air pollution are considered to among the most significant causes of lung cancer, yet people have been known to die of the disease without being smokers or having been exposed to significant pollution.

One particularly serious variety of respiratory illness is cystic fibrosis, a genetic disorder that causes a thick mucus to build up in the respiratory system and in the pancreas, a digestive organ. (For more about genetic disorders, see Heredity; for more on role of the pancreas, see Digestion.) In the United States, the disease affects about one in every 3,900 babies born annually. No cure for cystic fibrosis exists, and the disease is invariably fatal, with only about 50% of sufferers surviving into their thirties.

Lung complications are the leading cause of death from cystic fibrosis, and most symptoms of the disease are related to the sticky mucus that clogs the lungs and pancreas. People with cystic fibrosis have trouble breathing, and are highly susceptible to bacterial infections of the lungs. Coughing, while it may be irritating and painful if you have a cold, is necessary for the expulsion of infected mucus, but mucus in the lungs of a cystic fibrosis is too thick to be moved. This makes it easy for bacteria to inhabit the lungs and cause infection.

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NUTRITION

FOOD WEBS

NUTRIENTS AND NUTRITION

VITAMINS

FOOD WEBS

CONCEPT

The idea of a food chain is common in everyday life, so much so that it has become a metaphor applied in many situations. A high achiever in business or other endeavors is said to be "at the top of the food chain," and images of big fish eating little fish abound in cartoons. Yet in the study of the biological sciences, the concept of food chains is part of the much larger idea of a food web. Whereas a food chain is a linear series of organisms dependent on each other for food, a food web is an interconnected set of food chains in the same ecosystem. Food webs make possible the transfer of energy from plants through herbivores to carnivores and omnivores, and ultimately to the detritivores and decomposers that enrich the soil with organic waste. Just as a food web can transfer materials essential to the life of organisms, it is also a devastatingly efficient conduit for the transfer of poisons.

HOW IT WORKS

Food Webs in Context

An ecosystem is a community of independent organisms along with the inorganic components (chiefly soil, water, air, and rocks) that make up their environment. A biome is a large ecosystem, characterized by its dominant life-forms—for example, the Amazonian rain forest.

That portion of an ecosystem composed only of living things, as opposed to the formerly living or never living components, is known as a biological community. This community includes creatures from all five kingdoms of living organisms (including bacteria, algae, and fungi), whereas the term biota typically refers only to plant and animal life within a biological community or ecosystem. (For more on these subjects, see Ecosystems and Ecology and Biological Communities.)

Trophic Levels

The organisms in a biological community are linked in their need to obtain energy from food, which derives from the Sun through plant life. (There are, however, some communities, in areas such as deep-ocean rifts, that are not dependent on sunlight at all.) The Sun's energy is electromagnetic and travels in the form of radiation, which Earth receives as light and heat. Plants, known as primary producers, convert this electromagnetic energy into chemical energy through the process of photosynthesis.

The plants are eaten by herbivores (plant-eating animals), known also as primary consumers, examples of which include squirrels, rabbits, mice, deer, cows, horses, sheep, and seed-eating birds. These creatures, in turn, are eaten by secondary consumers, which are either carnivores, which are creatures that eat only meat, or omnivores—creatures, such as humans, that eat meat and plants.

There may even be tertiary, or third-level, consumers. These are animals that eat secondary consumers; examples are mountain lions and hawks, both of which eat such second-order consumers as snakes and owls. Human societies that eat dogs or cats, as well as those that engage in cannibalism, also behave as tertiary consumers. (See Biological Communities for a biological explanation of what otherwise is considered an abhorrent and immoral practice—not to men-

tion a dangerous one, due to the risk of such diseases as kuru, a type of spongiform encephalopathy.) In any case, the further along in the chain of trophic levels or stages of the food web, the fewer consumers there are.

Energy and trophic levels. It is fairly obvious that when a creature is "higher on the food chain" (to use the common expression), it has fewer natural predators. The reason for this is that at each successive trophic level, there are simply fewer organisms; this, in turn, is due to the fact that the energy available to each level is progressively smaller, and the organisms themselves progressively larger. *This,* in turn, stems from one of the most intriguing, maddening concepts in the entire universe: the second law of thermodynamics, which we discuss shortly.

Because of the diminishing number of organisms at each trophic level, the food web often is depicted as a pyramid, a concept we explore further later in this essay. The number of organisms begins to increase again at the next trophic level beyond secondary or tertiary consumers, that of decomposers. Large omnivores and carnivores may not be prey for other creatures in life, but everything dies eventually, and anything that has ever lived is food for detritivores, or organisms that feed on waste matter.

Detritivores and decomposers. Detritivores, which range in size and complexity from maggots to vultures, may not be the most appealing creatures on Earth, but without them life itself would suffer. By consuming the remains of formerly living things, they break organic material down into inorganic substances. In other words, their internal systems chemically process compounds containing the element carbon in characteristic structures. They then release that carbon into the atmosphere and soil in such a way that what remains is inorganic material that enriches the soil for the growth of new plant life.

But detritivores are not the last stop on the food web. The final trophic level, before the cycle comes back around to plants, contains the largest number of organisms in the entire food web—perhaps billions and billions, even in a space smaller than a coffee cup. These are decomposers, or organisms that, as with detritivores, obtain their energy from the chemical breakdown of dead organisms. The decomposers, however, break down the nutrients in decayed organic matter to a far greater extent than do detritivores.

Typically, decomposers are microorganisms, including bacteria and fungi, and they process materials in such a way that complex compounds undergo the chemical reaction of decomposition. Through decomposition, compounds are broken down into simpler forms, or even into their constituent elements, which provide the environment with nutrients necessary to the growth of more plant life.

Categorizing the trophic levels. The organisms in the food web can be viewed in three groups: producers (plants), consumers (primary- and secondary-consuming animals, whether herbivores, carnivores, or omnivores), and decomposers (that is, both detritivores and true decomposers). Producers and consumers are part of a larger structure known as the grazing food web, in which food is "on its way up the food chain," as it were. Decomposers and detritivores make up the decomposer food web, which brings food back "down" to the soil.

Producers also are called *autotrophs,* from Greek roots meaning "self-feeders," because they are not dependent on other organisms as a source of energy. Beyond the level of the primary producers, all consumers are known as *heterotrophs,* or "other-feeders." These creatures feed on other organisms to obtain their energy and are classified according to the types of food they eat—herbivores, carnivores, omnivores, as we already have discussed. Detritivores and decomposers also are considered heterotrophs.

Organisms and Energy

Rather than depending on other organisms for energy, autotrophs obtain energy from the Sun and carbon dioxide from the atmosphere. From these components, they build the large organic molecules that they need to survive. Green plants do this through the process of photosynthesis, a chemical reaction that can be represented as follows:

solar energy + carbon dioxide (CO_2) + water (H_2O) $\rightarrow$ glucose (sugar: $C_6H_{12}O_6$) + oxygen (O_2)

Actually, in order to produce what chemists call a *balanced equation,* it would be necessary to

show this equation as a reaction between the energy and six molecules each of carbon dioxide and water, which would produce a glucose molecule and six oxygen molecules. In any case, what we have described here is an amazing thing and one of the great wonders of nature. Sunlight aids plants in converting carbon dioxide, which they receive from the respiration of animals, along with water (which also may come from animal respiration, though this is not necessarily the case), into a sugar molecule for the plant's sustenance. Furthermore, oxygen, essential to the life of virtually all animals, also is produced—yet from the standpoint of the plant, it is simply a waste by-product!

THE SECOND LAW OF THERMODYNAMICS. The productivity of plants, which is measured in terms of biomass (the combined mass of all organisms at a particular trophic level in a food web), determines the amount of "fixed," or usable, energy available to other trophic levels on the food web. The amount of energy available always will be less for each successive trophic level, through the point where consumers end and decomposers begin—that is, through the level of the secondary or perhaps tertiary consumer.

If there is any scientific equivalent of the curse in the Garden of Eden (the punishment for the sins of Adam and Eve, according to Judeo-Christian belief), it is the second law of thermodynamics. Just as the expulsion from Paradise in the biblical story ensured that life would be much more difficult for humans than it would have been in Eden, so the second law thwarts all ambitions toward transcending the limits of physical reality.

The first law of thermodynamics states that it is impossible to obtain more energy from a system than is put into it. Thus, for instance, a car will go only as far as is allowed by the amount of energy that is pumped into its tank. The first law, discovered in the mid–nineteenth century, effectively ruled out any hopes of a perpetual-motion machine, but the second law, derived a few decades later, delivered even worse news.

Though it can be stated in a number of ways, the second law essentially means that it is impossible to extract as much energy from a system as one puts into it. Thus, in the case of an automobile, most of the energy contained in the gas does not go toward moving the car; rather, it is dissipated in the form of heat and sound, as a natural by-product of operating the engine. Even without running an air conditioner or other energy-consuming device, only about 30% of the energy from the gas goes to turning the wheels.

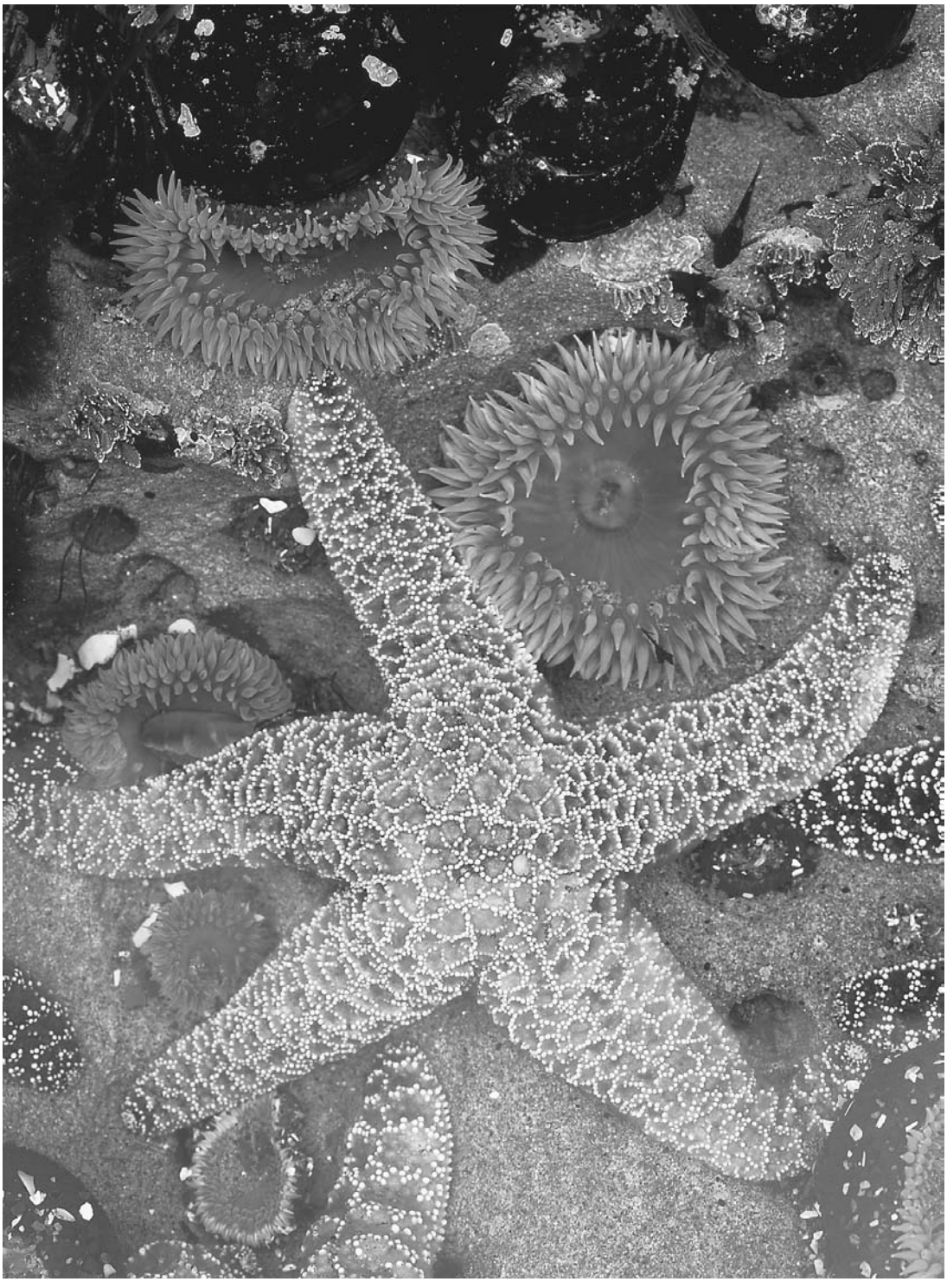
THE ECOLOGICAL PYRAMID. What this means for the food web is that there is bound to be a loss of energy in the transfer from one trophic level to another. Organisms never manage to retrieve 100% of the energy from the materials they eat; in fact, the figure is more like 10%. A rabbit that eats a carrot gets only about 10% of the energy in it, and an owl that eats the rabbit gets only about 10% of the energy from the rabbit, or 1% of the energy in the carrot. Because of these diminishing returns, there are always fewer organisms at each successive trophic level on the grazing food web. This fact is expressed in a model known as the *ecological pyramid,* or *energy pyramid,* which shows that as the amount of total energy decreases with each trophic level, so does the biomass. As a result, it may take 1,000 carrots to support 100 rabbits, 10 owls, and one hawk.

The picture changes as the shift is made from the grazing web to the decomposer web. Detritivores and decomposers are extraordinarily efficient feeders, reworking detritus over and over and extracting more fixed energy as they do. Eventually, they break the waste down into simple inorganic chemicals, which, as we have noted, then may be reused by the primary producers. The number of organisms in the decomposing food web dwarfs that of all others combined, though decomposers themselves are very small, and their combined population takes up very little physical space.

REAL-LIFE APPLICATIONS

Keystone Species

The keystone in an archway is a wedge-shaped stone at the top of the arch. It's position is extraordinarily important: if the keystone is removed, the arch will collapse. Thus, the keystone has become an often-used metaphor in other circumstances, as, for instance, in the nickname of Pennsylvania, the "Keystone State." In the realm of ecology, the term *keystone species* refers to those organisms that, like a keystone in



The term keystone species refers to an organism that plays a critical role in its environment, one that may become apparent only once it is removed from an ecosystem. On the west coast of North America, for instance, removal of a certain species of starfish caused a rapid growth in the numbers and biomass of the mussel upon which the starfish fed. *(© Stuart Westmorland/Corbis. Reproduced by permission.)*

architecture or engineering, play a critical role in their environments.

Within a food web, for instance, a keystone species can have a powerful influence, one that is far out of proportion to its relative biomass or productivity. Typically, a keystone species is a top predator (that is, a large secondary or even tertiary consumer), though occasionally an herbivore

can occupy the keystone position. Often, the role of the keystone species becomes apparent only once it is removed, either experimentally or by natural forces, from an ecosystem.

STARFISH AND MUSSELS. In temperate ecosystems on the west coast of North America, for instance, removal of a certain species of starfish (*Pisaster ochraceous*) was found to cause a rapid growth in the numbers and biomass of the mussel *Mytilus californianus.* The latter then forced out other species and proceeded to dominate the biological community. As it turned out, the starfish acted as a keystone predator by consuming these mussels.

Specifically, the starfish prevented the mussel from gaining dominance that it otherwise would have gained, owing to its competitive superiority in relation to other species within this particular coastal ecosystem. Yet the starfish could not eliminate the mussel, because it was incapable of feeding on larger individuals of that species. The result was that the community enjoyed a much greater degree of diversity and complexity than it would have if the mussel had been allowed to dominate.

SEA OTTERS AND KELP FORESTS. Another keystone species in a geographic area close to that of the starfish we have just described is the sea otter, native to western North America. Its principal food source is the sea urchin, an herbivore that, in turn, survives by consuming kelp, a large form of algae. By controlling the numbers and densities of sea urchins, sea otters allowed kelp to retain a relatively large biomass within the community, thus facilitating the growth of "kelp forests."

When humans began hunting sea otters for their fur during the late eighteenth and into the nineteenth centuries, however, the ecological effect soon was felt in the form of declining kelp forests. Fortunately, hunting did not render the species extinct, and since the 1930s, sea otters have been colonizing many of their former habitats. This colonization has resulted in a corresponding increase in the density of surrounding kelp forests.

INDICATOR SPECIES

A concept similar to that of the keystone species is the idea of an indicator species: plants or animals that, by their presence, abundance, or chemical composition, demonstrate a distinctive aspect of the character or quality of the environment. For instance, in an ecosystem affected by pollution, examination of indicator plant species may reveal the pollution patterns. By their presence, indicator species also may serve to show the quality or integrity of an ecosystem. Such is the case, for instance, with the spotted owl, or *Strix occidentalis,* and other species that depend on old-growth forests. (See Succession and Climax for more on this subject.) Because the needs of these species are so particular, their presence or absence can illustrate the health or lack thereof of the biome in question.

Other indicator plants also can be used to determine the presence of valuable mineral deposits in the soil, because those minerals make their way into the tissues of the plants themselves. Nickel concentrations as great as 10% have been found in the tissues of Russian plants from the mustard family, and a mintlike species called *Becium homblei* has proved useful for locating copper deposits in parts of Africa. Since the plant can tolerate more than 7% copper in soil (a great amount and many times the percentage of copper in the human body, for instance), it can and does live near enormous copper deposits.

INDICATING TOXINS. Some plants can serve as indicators of serpentine minerals, varieties of compounds that can be toxic in large concentrations. In California, for instance, where serpentine soils are not uncommon, there plant species unique to specific ecosystems high in serpentine mineral content. Elsewhere, there are types of lichens that are sensitive to toxic gases, such as sulfur dioxide, and thus these lichens can be monitored as a way of keeping tabs on air pollution.

In semiarid regions where soils contain large quantities of the element selenium, plants can accumulate such large concentrations of the element that they become poisonous to primary consumers (for example, rabbits) who eat them. The result may be temporary or even permanent blindness. In such situations, legumes of the genus *Astragalus,* which can accumulate as much as 15,000 ppm (parts per million)—a comparatively enormous concentration—serve as indicators. Their heavy selenium concentration gives them a noticeably unpleasant smell.

Aquatic invertebrates and fish often have been surveyed for what they can show as to the quality of water and the health of aquatic ecosys-



Beachgoers are sprayed with DDT in the first public test of a new machine for distributing the insecticide in 1945. Once pesticides such as DDT have been sprayed in a region, rain can wash them into creeks, lakes, and other bodies of water, where they are absorbed by creatures that either drink or swim in the water and thus enter the food web. *(© Bettmann/Corbis. Reproduced by permission.)*

tems. The presence of a creature known by the disgusting name sewage worm, or tubificid worm (*Tubificidae*), indicates the degradation of water quality by the introduction of sewage or other outside organic matter that consumes oxygen. Tubificid worms are virtually anaerobic, or non-oxygen-breathing, unlike the animals that would occupy a similar niche in a healthy aquatic environment.

Bioaccumulation and Biomagnification

The subject of indicator species leads us, naturally enough, to the topic of pollution in the food web, which can be seen on a small scale in the phenomenon of bioaccumulation and which manifests on a much broader scale as biomagnification. One of the key concepts in ecological studies is the idea that a disturbance in one area can lead to serious consequences elsewhere. The interconnectedness of components in the environment thus makes it impossible for any event or phenomenon to be truly isolated.

Nowhere is this principle better illustrated that in the processes of bioaccumulation and biomagnification. The first of these is the buildup of toxins, and particularly chemical pollutants, in the tissues of individual organisms. Part of the danger in these toxins is the fact that the organism cannot easily process them either by metabolizing them (i.e., incorporating them into the metabolic system, as one does food or water) or by excreting them through urine or other substances produced by the body.

The only way for the organism to release toxins, in fact, is by passing them on to other members of the food web. Because organisms at each successive trophic level must consume more biomass to meet their energy requirements, they experience an increase in contamination, a phenomenon known as biomagnification. The following example illustrates how toxins enter the food web and gradually make their way down the line, growing in proportion as they do.

Particles of pollutant may stick to algae, for instance, which are so small that the toxin does little damage at this level of the food web. But even a small herbivore, such as a zooplankton, takes in larger quantities of the pollutant when it consumes the algae, and so begins the cycle of biomagnification. By the time the toxin has passed from a zooplankton to a small fish, the

amount of pollutant in a single organism might be 100 times what it was at the level of the algae. The reason, again, is that the fish can consume 10 zooplankton that each has consumed 10 algae.

These particular numbers, of course, are used simply for the sake of convenience, as were those cited earlier in relation to the ecological pyramid. Note, incidentally, the similarity of the relationships between this "pyramid of poison" and the ecological pyramid, whereby energy, which is beneficial, passes between trophic levels. The higher the trophic level, the smaller the amounts of energy that the organism extracts from its food—but the higher the amount of toxic content. By the time the toxins have passed on to a few more levels in the food web, they might be appearing in concentrations as great as 10,000 times their original amount.

DDT BIOMAGNIFICATION. Among the most prominent examples of chemical pollutants that are bioaccumulated are such pesticides as DDT (dichlorodiphenyltrichloroethane). DDT is an insecticide of the hydrocarbon family, a large group of chemical compounds of which the many varieties of petroleum are examples. Because it is based in hydrocarbons, DDT is hydrophobic ("water-fearing") and instead mixes with oils—including the fat of organisms.

In the twenty or so years leading up to 1972, Americans used vast amounts of DDT for the purpose of controlling mosquitoes and other pests. DDT appeared to be a remarkably successful killer, and in fact it turned out to be a little too successful. As it found its way into water sources, DDT entered the bodies of fish, and then those of predatory birds such as osprey, peregrine falcons, brown pelicans, and even the bald eagle.

The detrimental effect of DDT on America's national symbol, a bird protected by law since 1940, aptly illustrates the ravages exacted by this powerful insecticide. DDT levels in birds became so high that the birds' eggshells were abnormally thin, and adult birds sitting on the nest would accidentally break the shells of unhatched chicks. As a result, baby birds died, and populations of these species dwindled. Environmentalists in the late 1960s and early 1970s raised public awareness of this phenomenon, and this led to the banning of DDT spraying in 1972. The period since that time has seen dramatic increases in bird populations.

THE HUMAN FACTOR. Because the species of bird affected were not ones that people normally consume for food, DDT biomagnification did not have a wide-ranging effect on human populations. However, tests showed that some DDT had made its way into the fat deposits of some members of the population. In any case, bioaccumulation and biomagnification have threatened humans, for instance in the late 1940s and early 1950s, when cows fed on grass that had been exposed to nuclear radiation, and this radioactive material found its way into milk.

Traces of the radioactive isotope strontium-90, a by-product of nuclear weapons testing in the atmosphere from the late 1940s onward, fell to earth in a fine powder that coated the grass. Later the cows ate the grass, and strontium-90 wound up in the milk they produced. Because of its similarities to calcium, the isotope became incorporated into the teeth and gums of children who drank the milk, posing health concerns that helped bring an end to atmospheric testing in the early 1960s.

Humans themselves can serve as repositories for contaminants, a particular concern for a mother nursing her baby. Assuming the mother's own system has been contaminated by toxins, it is likely that her milk contains traces of the harmful chemical, which will be passed on to her child. Obviously, this is a very serious matter. Nursing mothers, babies, and their loved ones are not the only people affected by bioaccumulation and the storing of toxins in fatty tissues. In fact, some physicians and nutritionists maintain that one of the reasons for the buildup of fat on a person's body (though certainly not the only reason) may be as a response to toxins, the idea being that the body produces fat cells as a means of keeping the toxins away from the bloodstream.

Another case of large-scale bioaccumulation occurred during the 1970s and 1980s, when fish such as tuna were found to contain bioaccumulated levels of mercury. In the face of such concerns, governments have intervened in several ways, including the banning of DDT spraying, as mentioned earlier. The U.S. federal government and the governments of some states have issued warnings against the consumption of certain types of fish, owing to bioaccumulated levels of toxic pollutants. Bioaccumulation is particularly serious in the case of species that live a long time,

KEY TERMS

AUTOTROPHS: Primary producers. *Autotroph* means "self-feeder," and these organisms are distinguished by the fact that they do not depend on other organisms as a source of energy. Instead, they obtain energy from the Sun and carbon dioxide from the atmosphere, and from these constituents they build the large organic molecules that they need to survive.

BIOACCUMULATION: The buildup of toxic chemical pollutants in the fatty tissues of organisms.

BIOGEOCHEMICAL CYCLES: The changes that particular elements undergo as they pass back and forth through the various earth systems (e.g., the biosphere) and particularly between living and nonliving matter. The elements involved in biogeochemical cycles are hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur.

BIOLOGICAL COMMUNITY: The living components of an ecosystem.

BIOMAGNIFICATION: The increase in bioaccumulated contamination at higher levels of the food web. Biomagnification results from the fact that larger organisms consume larger quantities of food—and, hence, in the case of polluted materials, more toxins.

BIOMASS: The combined mass of all organisms at a particular trophic level in a food web.

BIOME: A large ecosystem, characterized by its dominant life-forms.

BIOSPHERE: A combination of all living things on Earth—plants, mammals, birds, amphibians, reptiles, aquatic life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

BIOTA: A combination of all flora and fauna (plant and animal life, respectively) in a region.

CARNIVORE: A meat-eating organism, or an organism that eats *only* meat (as distinguished from an omnivore).

DECOMPOSER FOOD WEB: That portion of the food web occupied by detritivores and decomposers. (Compare with *grazing food web.*)

DECOMPOSERS: Organisms that obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. The principal forms of decomposer are bacteria and fungi.

DECOMPOSITION REACTION: A chemical reaction in which a compound is broken down into simpler compounds, or into its constituent elements. In the biosphere, this often is achieved through the help of detritivores and decomposers.

DETRITIVORES: Organisms that feed on waste matter, breaking organic material down into inorganic substances that then can become available to the biosphere in the form of nutrients for plants. Their function is similar to that of decomposers; however, unlike decomposers—which tend to be bacteria or fungi—detritivores are relatively complex organisms, such as earthworms or maggots.

ECOLOGY: The study of the relationships between organisms and their environments.

KEY TERMS CONTINUED

ECOSYSTEM: A community of interdependent organisms along with the inorganic components of their environment.

ENERGY TRANSFER: The flow of energy between organisms in a food web.

FIRST LAW OF THERMODYNAMICS: A law of physics stating that the amount of energy in a system remains constant, and therefore it is impossible to perform work that results in an energy output greater than the energy input.

FOOD CHAIN: A series of singular organisms in which each plant or animal depends on the organism that precedes it. Food chains rarely exist in nature; therefore, scientists prefer the term *food web.*

FOOD WEB: A term describing the interaction of plants, herbivores, carnivores, omnivores, decomposers, and detritivores in an ecosystem. Each of these organisms consumes nutrients and passes them along to other organisms (or, in the case of the decomposer food web, to the soil and environment). The food web may be thought of as a bundle or network of food chains, but since the latter rarely exist separately, scientists prefer the concept of a food web to that of a food chain.

GRAZING FOOD WEB: That portion of the food web occupied by autotrophs, herbivores, carnivores, and omnivores. (Compare with *decomposer food web.*)

HERBIVORE: A plant-eating organism.

HETEROTROPHS: Secondary consumers, or "other-feeders." These creatures feed on other organisms to obtain their energy and are classified according to the types of food they eat. Thus, they are known as herbivores, carnivores, and so on.

INDICATOR SPECIES: A plant or animal that, by its presence, abundance, or chemical composition, demonstrates a particular aspect of the character or quality of the environment.

KEYSTONE SPECIES: A species that plays a crucial role in the functioning of its ecosystem or that has a disproportionate influence on the structure of its ecosystem.

NICHE: A term referring to the role that a particular organism plays within its biological community.

OMNIVORE: An organism that eats both plants and other animals.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals) and oxides, such as carbon dioxide.

PHOTOSYNTHESIS: The biological conversion of light energy (that is, electromagnetic energy) from the Sun to chemical energy in plants.

PRIMARY CONSUMERS: Animals that eat green plants. (Compare with *secondary consumers.*)

PRIMARY PRODUCERS: Green plants that depend on photosynthesis for their nourishment.

SECONDARY CONSUMERS: Animals that eat other animals.

SECOND LAW OF THERMODYNAMICS: A law of physics, which can be stat-

KEY TERMS CONTINUED

ed in several ways, all of which mean the same thing. According to one version of the second law, it is impossible to transfer energy with perfect efficiency, because some energy always will be lost in the transfer. This is the same as saying that it is impossible to extract from a system the same amount of energy that was put into it.

TROPHIC LEVELS: Various stages within a food web. For instance, plants are on one trophic level, herbivores on another, and so on.

because a longer life allows for much longer periods of bioaccumulation. For this reason, some governments warn against consuming fish over a certain age or size: the older and larger the creature, the more contaminated it is likely to be.

WHERE TO LEARN MORE

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NUTRIENTS AND NUTRITION

CONCEPT

In the modern world people are accustomed to hearing a great deal about nutrients and nutrition. Words such as protein, carbohydrate, vitamins, minerals, and fats are a regular part of daily life, yet few people who talk about these nutrients really know what they are. In fact, these are the basic building blocks of nutrition, whereby animal life is sustained. Whereas plants can get their energy directly from the Sun and the atmosphere, animals (including humans) depend on other organisms to provide them with nutrition. These other organisms include plants, which generate carbohydrates as a result of photosynthesis, as well as other animals that eat plants and thereby build proteins and fats. Plants also may contain proteins and fats, and both plants and animals contain vitamins and minerals. These nutrients, consumed in the proper forms and proportions, sustain life and prevent the miseries of malnutrition—a condition that can involve either undernourishment or overnourishment.

HOW IT WORKS

Nutrients and Nutrition

In order to live, animals must consume nutrients, of which there are five major classes: carbohydrates, proteins, lipids or fats, vitamins, and minerals. In addition to these constituents, of course, animal life requires other materials for its sustenance-water, oxygen, and fiber, which aids in the digestive processing of foods-but these components usually are not regarded as nutrients.

Nutrition itself is the series of processes by which an organism takes in nutrients and makes use of them for its survival, growth, and development. The term nutrition also can refer to the study of nutrients, their consumption, and their processing in the bodies of organisms. Here the general term organism has been used, but for the most part the present essay is concerned with animal nutrition, or at least the nutrition of primary consumers (animals that eat plants) and secondary consumers (animals that eat other animals).

AUTOTROPHS AND THEIR NUTRIENTS. By contrast, plants and a few other types of organism are autotrophs, or primary producers in the food web. Autotroph means "self-feeder," and these organisms are distinguished by the fact that they do not depend on other organisms as a source of energy. Instead, plants obtain energy from the Sun and carbon dioxide from the atmosphere, and from these materials they build the large organic molecules that they need to survive.

Though plants are the most obvious example of an autotroph, they are not the only ones. In the deep oceans, far from any plant life, primary consumers depend on phytoplankton, which are microscopic organisms that encompass a range of bacteria and algae. Nonplant autotrophs may use means different from those employed by plants in generating their own food. For example, there are certain nonplant autotrophic organisms that live in the deep oceans near hydrothermal vents, which are cracks in the ocean floor caused by volcanic activity. These organisms, unlike most autotrophs, do not need sunlight to survive. Instead, they build their own nutrients in a sunless world, using sulfur compounds found near the vents.

Chemical Elements and Nutrition

An element is a chemical substance made of only one kind of atom, whereas in a compound, atoms of more than one element are chemically bonded to one another. Unlike compounds, elements cannot be broken chemically into other substances. There are approximately 90 elements that occur in nature, and many of these elements—but not nearly all—are important to nutrition.

Elements in the human body and biogeochemical cycles. Even when we rule out obviously harmful elements, such as lead or uranium, there are still numerous chemical elements that play a part in the nutrition of living things. This can be illustrated by a glance at the abundance of various chemical elements in the human body, which include oxygen, carbon, and hydrogen. Oxygen alone accounts for a whopping 65% of the human body's mass, and carbon (18%), hydrogen (10%), and oxygen together make up 93% of the mass in the human body.

A great deal of oxygen and hydrogen, of course, is found in that most useful of all chemical compounds, water. In this vein, it should be noted that all the elements that take part in biogeochemical cycles, which are essential to the functioning of Earth, appear in relatively large proportions within the human body. These elements are hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur. (For more about biogeochemical cycles and the elements involved in them, including their proportion within the human body's mass, see The Biosphere.)

Carbon is present in all living things, and its presence in certain forms is key to distinguishing organic from inorganic substances. Contrary to popular belief, organic substances are not just living things, their parts, and their products. Something that has never been living still can be considered organic, provided that it contains compounds that include carbon. (The only exceptions would be carbonates and carbon oxides, two groups of carbon-based compounds that are excluded from the ranks of organic substances.) As we shall see, carbon, along with oxygen and hydrogen, plays a key role in nutrition.

Most of the remaining 7% of the body's mass is composed of ten other elements. Among these elements are the other three involved in biogeochemical cycles, whose names are italicized: *nitrogen* (3%), calcium (1.4%), *phosphorus* (1.0%), magnesium (0.50%), potassium (0.34%), *sulfur* (0.26%), sodium (0.14%), chlorine (0.14%), iron (0.004%), and zinc (0.003%). Note that many of these elements are found in vitamin and mineral supplements that people might take on a daily basis to augment the essential nutrients in their bodies. There are exceptions, however, such as sodium, of which most people already ingest too much in the form of salt.

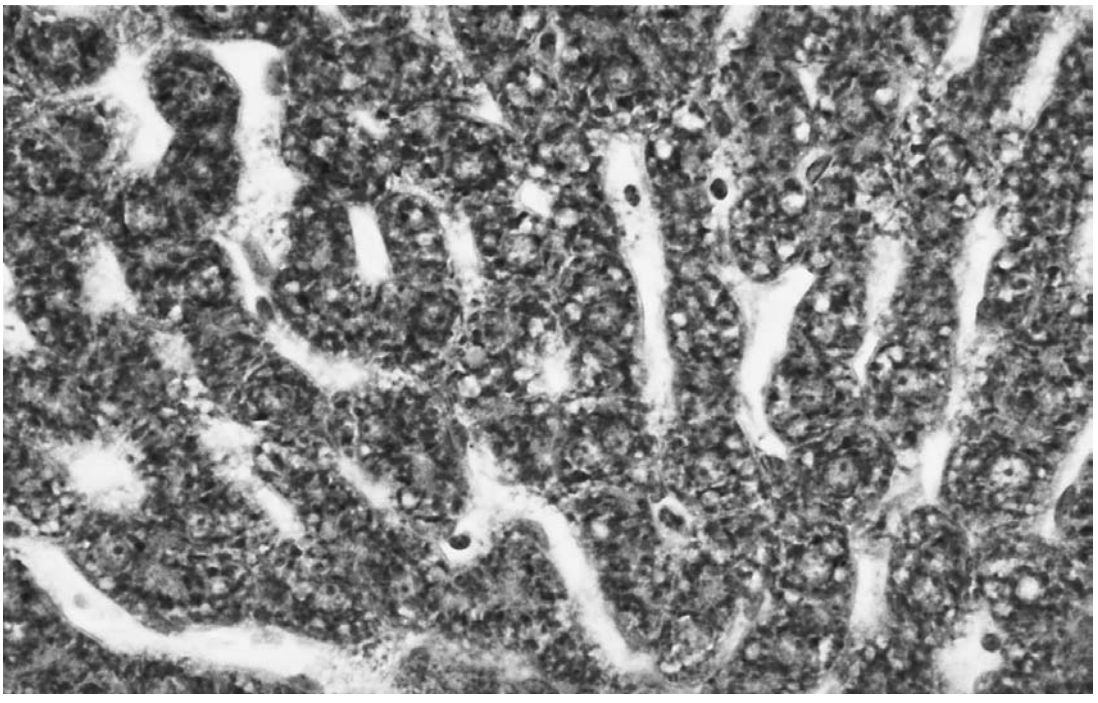
Trace elements. Generally speaking, it is safe to assume that any element that appears naturally in the human body is healthful as a nutritional component. This rule of thumb goes only so far, however: chlorine, for instance, is poisonous in large quantities, whereas in the very small proportions found in the human body, it can be essential to health and well-being. It is certainly possible to ingest some elements in unhealthy quantities, a fact that is particularly true of trace elements.

Copper is an example of a trace element, so named because only traces of them are present in the human body. In tiny quantities, copper is beneficial to human health, but if that small amount is exceeded, the effects can run the gamut from sneezing to diarrhea. In the proper proportions, however, trace elements are essential: without enough iodine, for instance, goiter, a large swelling of the thyroid gland in the neck area, can develop. Chromium helps the body metabolize sugars, which is why people concerned with losing weight or toning their bodies through exercise may take a chromium supplement. Even arsenic, which is lethal in large quantities, is a trace element in the human body, and medicines for treating such illnesses as "sleeping sickness" contain tiny amounts of arsenic. Other trace elements include cobalt, fluorine, manganese, molybdenum, nickel, selenium, silicon, and vanadium.

Real-Life Applications

Nutrients

If you glance at the side of a cereal box, or virtually any other food product manufactured in the United States, chances are that you will see a table



When a person ingests more carbohydrates than the body needs, the body converts the excess into a compound known as glycogen. It then stores the glycogen in the liver (shown here) and muscle tissues, where it remains, a potential source of energy for the future. *(© Lester V. Bergman/Corbis. Reproduced by permission.)*

listing proportions of nutrients per serving. This is the "Nutrition Facts" label, which replaced the old "Nutrition Information Per Serving" label in the early 1990s. Both forms of information label were administered by the United States Food and Drug Administration (FDA), with the newer labeling format being far more extensive in terms of the information it provides.

Usually these tables show the amount of nutrients both in terms of mass (usually rendered in metric components, such as grams or milligrams) and as a proportion of recommended daily value according to the FDA. These listings must include information about some components such as calories, fat, sodium, sugars, certain vitamins, and so on. In addition to these mandatory listings, labels may contain information that the manufacturer chooses to provide concerning other food components, such as potassium or insoluble fiber.

Today, even fast-food restaurants such as McDonald's, which is probably not the first name that comes to mind when one thinks of healthy eating, provide extensive nutritional information to customers. Additionally, makers of fast food or supermarket "junk food" such as potato chips have introduced offerings that represent a nod to nutritional concerns. These include products that are fat- or sodium-free, or are otherwise geared toward greater health consciousness.

Clearly, diet is a significant concern to Americans, the most well-fed group of people that has ever existed, and terms from the Nutrition Facts label—proteins, carbohydrates, fats, minerals, and vitamins—are household words, known to almost everyone but understood by only a few. In much of the remainder of this essay, we explore these concepts, discussing what they mean in very basic scientific terms, as well as in terms of their significance in the diets of humans and other animals.

PROTEINS. Proteins are large molecules built from long chains of amino acids, which are organic compounds made of carbon, hydrogen, oxygen, nitrogen, and (in some cases) sulfur bonded in characteristic formations. Proteins serve the functions of promoting normal growth, repairing damaged tissue, contributing to the body's immune system, and making enzymes. (An enzyme is a protein material that speeds up chemical reactions in the bodies of plants and animals.)

Proteins in the human body contain about 20 different amino acids, of which the body is able to manufacture 12 from the foods we eat. The other eight, which the body requires for protein production but is unable to manufacture on its own, are known as the *essential amino acids.* When a protein contains all of the essential amino acids, it is known as a complete protein. Among the best forms of complete protein are fish, red meat, and poultry as well as eggs, milk, cheese, and other dairy products. Fittingly, a protein that lacks at least one of the essential amino acids is known as an incomplete protein. Examples include peas, beans, lentils, nuts, and cereal grains. These can, however, be combined in such a way as to make a complete protein, beans and rice being a good example.

CARBOHYDRATES. Carbohydrates are natural compounds that consist of carbon, hydrogen, and oxygen and whose primary function in the body is to supply energy. When a person ingests more carbohydrates than his or her body needs at the moment, the body converts the excess into a compound known as glycogen. It then stores the glycogen in the liver and muscle tissues, where it remains, a potential source of energy for the body to use in the future.

Sugars, starches, cellulose, and various other chemically related substances are part of the carbohydrate group. Most carbohydrates are produced by green plants in the process of undergoing photosynthesis. Nutritionally, the carbohydrates include sugar in its various forms as well as another class of food that people do not always think of as carbohydrates: fruits. Additionally, such starchy foods as potatoes, rice, and wheat products (bread, pasta, and so on) rank as important carbohydrates, while cereal grains and corn are examples of foods that contain both starchy carbohydrates and proteins.

LIPIDS. All fats and oils are lipids; these substances are distinguished by the fact that they are soluble only in compounds made of nonpolar molecules. Water is an example of a polar molecule, because the oxygen and hydrogen atoms tend to occupy opposite "ends" of the molecule, with one end exerting a negative electric charge and the other end a positive one. Therefore, water molecules tend to stick closely together. On the other hand, oil molecules, which consist of carbon and hydrogen, are nonpolar, because the atoms of the two elements do not tend to drift to opposite ends of the molecule. As a result, oil has the slippery texture for which it is known.

With their affinity for nonpolar molecules, lipids are soluble, or capable of dissolving, in oily or fatty substances but not in water. In the body, lipids, like carbohydrates, supply energy, only in different ways and on a different timetable. When burned, a gram of lipid actually produces about three times as much energy as a gram of carbohydrate, but this energy release takes place much more slowly. Among the other functions performed by lipids in the body are protection of organs from shock and damage and the provision of insulation for the body, for instance, from toxins. (It is for this reason that toxins often are stored in fat cells. See Food Webs for more about DDT bioaccumulation in the fat cells of animals.)

VITAMINS AND MINERALS. Vitamins are organic substances that, in extremely small quantities, are essential to the nutrition of most animals and some plants. In particular, they work with enzymes in regulating metabolic processes, but they do not in themselves provide energy; thus, vitamins alone do not qualify as a form of nutrition. Much the same is true of minerals, except that they are inorganic substances. And whereas vitamins are usually chemically complex (the formula for vitamin A, for instance, is $C_{20}H_{29}OH$), minerals may be as simple as a single element—for instance, iron or calcium.

Though the body can produce some vitamins, in general, vitamins and minerals are substances that the body is incapable of making for itself. Therefore, for optimal health, it is necessary to include them in the diet on a regular, if not daily, basis. They also have in common the fact that the body needs them only in very small quantities, for which reason they are sometimes known as micronutrients.

Vitamin A, for example, is a substance necessary to the functioning of the eye's retina in adjusting to light, and thus proper vitamin A levels are essential for night vision. Without vitamin A, a person can be afflicted with a condition known as night blindness, as well as with dryness of the skin. Vitamin A is also essential to bone growth. This vitamin occurs naturally in such foods as green and yellow vegetables, eggs, fruits, and liver and particularly in fish liver oils, such as cod liver oil.

Calcium, a mineral, helps build strong bones and teeth. It also has a role in the normal functioning of nerve and muscle activity. Ninety-nine percent of the body's calcium is stored in the skeleton and teeth, while the remainder circulates in the bloodstream, where it helps make possible muscle contractions. Bones are 70% calcium by weight, which gives them their strength and rigidity. Calcium, which is even more prevalent than iron, is the most abundant metallic element in the human body. Good dietary sources of calcium include milk and milk products, eggs, such leafy green vegetables as spinach, and sardines.

The U.S. Department of Agriculture Food Pyramid

The U.S. Department of Agriculture (USDA) has developed a diagram, called the *food pyramid,* to illustrate the components needed in a healthy diet. The bottom and widest level of the pyramid contains the cereal foods, such as breads, pastas, and rice. Primarily carbohydrates, these foods are a major source of energy, and therefore the USDA recommends 6-11 servings of 1-2 oz (30–60 g) from this food group. As to the exact number of servings, this is a function of such variables as age, gender, weight, and degree of regular physical activity.

The second level of the food pyramid, which is smaller than the first, consists of fruits and vegetables. These foods, which are also primarily carbohydrates, are especially important in supplying vitamins and minerals. A secondary function is the delivery of indigestible fiber, which improves the functioning and health of the large intestine, or colon. From this group, the USDA recommends 5-9 servings a day.

At the third level of the pyramid are proteins, including meats, eggs, beans, nuts, and milk products. According to the USDA, the percentage of these foods in one's diet should be much smaller than the percentage of carbohydrates. Smaller still is the quantity of servings at the top level, which contains the lipids. The small space allotted to this food emphasizes the fact that fats and oils should be consumed in small quantities for optimum health.

Fat and the American Diet

What we have just described is the orthodox view of nutrition in the United States as the nation entered the twenty-first century. By that time, however, physicians, nutritionists, dieticians, and other specialists had begun to question the emphasis on carbohydrates in the USDA food pyramid and other mainstream diets. For a young person, whose body is still growing, the food pyramid is a good dietary plan. But for a person past the early twenties, particularly those who are overweight or suffering from a condition such as diabetes, other approaches may be needed.

The average American adult is considerably overweight for his or her height and age group, a fact for which a number of practices can be blamed. Among these practices are inactivity. Things have changed a great deal since our ancestors spent their whole lives in a flurry of physical activity, hunting animals for food and remaining ever on the move. Our bodies themselves—a product of natural selection that took place over countless generations (see Evolution)—know nothing about this change. They are still programmed to perform as they did 10,000 years ago, storing fat for use in lean times.

Thus, inactivity breeds obesity, a condition that cannot be addressed successfully by diets aimed simply at reducing consumption. In such a situation, the body simply holds on to its fat more fiercely, and this is one reason why a starvation diet is less than useless as a means of bringing about healthy weight loss. Starving oneself also reduces lean muscle mass, which further slows the metabolism and makes it still harder to burn fat. In fact, one of the best ways to lose weight is by combining resistance exercise (i.e., weight lifting) with proper eating.

Then, of course, there are the things Americans eat: junk food and fried foods, for instance. Eating junk food, pumped full of chemicals and white sugar, is like dumping garbage into a gas tank. As for fried foods, an American seldom realizes how much is in his or her diet until making a visit overseas. In Germany, for instance, virtually nothing is fried, and though people eat hearty meals with plenty of sausage, potatoes, bread, and beer, obesity is far less of a problem in Germany than in America. (Furthermore, the American traveler is likely to have far better bowel movements on the high-fiber German diet than on the greasy, fatty, salty American diet.)

The Case for Proteins

As healthy as a diet based on the food pyramid is, an overweight adult who stuck religiously to it



The average American adult is considerably overweight, a result of inactivity coupled with poor diet. Things have changed a great deal since our ancestors spent their lives in a flurry of physical activity, hunting animals for food and ever on the move, but the human body is still programmed to perform as it did 10,000 years ago, storing fat for use in lean times. *(© Bettmann/Corbis. Reproduced by permission.)*

most likely would remain overweight, even if he or she combined it with a regular program of aerobic exercise (e.g., jogging). Thus, by the late twentieth century, numerous experts across a wide spectrum of health professions began to challenge the old orthodoxy that held up carbohydrates as the central component of a healthy diet. Instead, a growing body of opinion favored diets that rely more on proteins and even healthy fats, such as those in broiled or grilled salmon or olive oil.

Whereas carbohydrate consumption can help an athlete gain a burst of energy, for most people carbohydrates are simply the raw materials for fat, which the body will store when it discovers that it does not need the carbohydrates themselves as an immediate source of energy. Furthermore, the brain has a mechanism for signaling the body that it has consumed enough protein, whereas there is no such mechanism where carbohydrates are concerned. To test this, try eating a meal of just protein: chances are that you will feel you have had enough fairly quickly. On the other hand, try eating a meal of just starches; you will find that you can eat and eat and eat, piling on calories as you do.

Malnutrition

As we noted earlier, corn has both protein and carbohydrate components, but this does not mean that a diet heavy in corn and corn products is a healthy one. Such a diet was not uncommon among poor people in the American South during the late nineteenth and the early twentieth centuries and among even poorer people in Mexico and other parts of Latin America to the present day. With Southern foods, such as grits, hominy, and cornbread, and Latin American foods, such as corn tortillas and polenta, it is quite possible to eat cheaply from a diet that relies primarily on corn. Yet someone who does so is at risk of serious health problems, because corn is lacking in two essential amino acids, lysine and tryptophan.

This is just one example of malnutrition, a condition that develops when the body does not obtain the right amount of the vitamins, minerals, and other nutrients it needs to maintain healthy tissues and organ function. Malnutrition occurs in people who are either undernourished or overnourished. Undernourishment is a consequence of consuming too few essential nutrients or using or excreting them more rapidly than

KEY TERMS

AMINO ACIDS: Organic compounds composed of carbon, hydrogen, oxygen, nitrogen, and (in some cases) sulfur bonded in characteristic formations. Strings of amino acids make up proteins.

AUTOTROPHS: Primary producers. *Autotroph* means "self-feeder," and these organisms are distinguished by the fact that they do not depend on other organisms as a source of energy. Instead, they need only sunlight, water, and a few simple chemical compounds, from which they build the large organic molecules that they need to survive.

BIOGEOCHEMICAL CYCLES: The changes that particular elements undergo as they pass back and forth through the various earth systems (e.g., the biosphere) and particularly between living and nonliving matter. The elements involved in biogeochemical cycles are hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur.

CARBOHYDRATES: Naturally occurring compounds, consisting of carbon, hydrogen, and oxygen, whose primary function in the body is to supply energy. Included in the carbohydrate group are sugars, starches, cellulose, and various other substances. Most carbohydrates are produced by green plants in the process of undergoing photosynthesis.

COMPLETE PROTEIN: A protein that includes all eight essential amino acids.

COMPOUND: A substance in which atoms of more than one element are bonded chemically to one another.

ELEMENT: A substance made up of only one kind of atom. Unlike compounds, elements cannot be broken down chemically into simpler substances.

ENZYME: A protein material that speeds up chemical reactions in the bodies of plants and animals.

ESSENTIAL AMINO ACIDS: Amino acids that cannot be manufactured by the body and which therefore must be obtained from the diet. Proteins that contain essential amino acids are known as *complete proteins.*

FOOD WEB: A term describing the interaction of plants, herbivores, carnivores, omnivores, decomposers, and detritivores in an ecosystem. Each of these organisms consumes nutrients and passes them along to other organisms (or, in the case of the decomposer food web, to the soil and environment). The food web may be thought of as a bundle or network of food chains, but since the latter rarely exist separately, scientists prefer the concept of a food web to that of a food chain.

LIPIDS: Fats and oils. With their affinity for nonpolar molecules, lipids dissolve in oily or fatty substances but not in water-based liquids. In the body, lipids supply energy in slow-release doses, protect organs from shock and damage, and provide insulation for the body, for instance, from toxins.

MALNUTRITION: Any one of several conditions that develop when the body does not obtain the right amount of vitamins, minerals, and other nutrients it needs to maintain healthy tissues and organ function. Malnutrition may result from undernourishment *or* overnourishment.

KEY TERMS CONTINUED

MINERALS: Inorganic substances that, in a nutritional context, serve a function similar to that of vitamins. Minerals may include chemical elements—particularly metallic ones, such as calcium or iron—as well as some compounds.

NUTRIENT: Materials essential to the survival of organisms. They include proteins, carbohydrates, lipids (fats), vitamins, and minerals.

NUTRITION: The series of processes by which an organism takes in nutrients and makes use of them for its survival, growth, and development. The term *nutrition* also can refer to the study of nutrients, their consumption, and their use in the organism's body.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals), and oxides, such as carbon dioxide.

PHOTOSYNTHESIS: The biological conversion of light energy (that is, electromagnetic energy) from the Sun to chemical energy in plants. In this process carbon dioxide and water are converted to sugars.

PRIMARY CONSUMERS: Animals that eat green plants. Compare with *secondary consumers.*

PRIMARY PRODUCERS: Green plants that depend on photosynthesis for their nourishment.

PROTEINS: Large molecules built from long chains of amino acids. Proteins serve the functions of promoting normal growth, repairing damaged tissue, contributing to the body's immune system, and making enzymes.

SECONDARY CONSUMERS: Animals that eat other animals.

TRACE ELEMENT: A chemical element that appears within an organism or other natural system in very small quantities, or traces. In the human body, for instance, such trace elements as copper or iodine are essential to health, though they comprise far less than 1% of the body's mass.

VITAMINS: Organic substances that, in extremely small quantities, are essential to the nutrition of most animals and some plants. In particular, vitamins work with enzymes in regulating metabolic processes; however, they do not in themselves provide energy, and thus vitamins alone do not qualify as a form of nutrition.

they can be replaced. This brings about the all-too-familiar scenarios most of us associate with malnutrition: scenes of starving children in the third world, their bellies distended from kwashiorkor (which we discuss next) and thus abnormally large, far out of proportion to their bony arms and legs.

Such scenes of horror, and the virtually unimaginable misery of which they provide a hint, are almost beyond the comprehension of the average American. In America even the poorest of people are reasonably well fed, certainly compared with the poor of Africa, Asia, or Latin America. But that does not mean that malnutrition is not a problem in the affluent Western world. In the United States undernourishment may not be nearly as much of a problem, but dietary imbalances and excesses are, and they have become associated with many of the leading causes of death and disability. Overnutrition

results from eating too much, eating too many of the wrong things (including junk foods, especially those containing white sugar), not exercising enough, or taking too many vitamins or other dietary replacements. As with many things, where vitamins are concerned, it is not the case that if a little is good, a lot is better. Vitamins can only be absorbed by the body if ingested on a full stomach, and an excess of fat-soluble vitamins such as A or D could actually be toxic. (See Vitamins for more on this subject.)

KWASHIORKOR. For any nutrient that the body requires, there is a corresponding disease, ailment, or condition (or many of them) that will develop if a person's body is deprived of that nutrient. For instance, people whose diets lack protein may become susceptible to a condition known as *kwashiorkor,* characterized by apathy, exhaustion, fatigue, wasting of muscle tissue, and edema (swelling, a result of water collecting in the body.)

Kwashiorkor, in fact, is the condition that causes swelling in the stomachs of children suffering from malnutrition. When people eat a diet consisting mainly of starchy vegetables, as is common in parts of Africa, Latin America, and southern Asia, they consume an appropriate amount of calories, but they do not get certain essential amino acids that are important for growth. This is particularly serious for children. Nursing babies usually do not suffer from kwashiorkor, because they receive adequate protein from their mother's milk. A child who is weaned, however, is at much greater risk.

In much of the third world, where human populations are high relative to the number of animals raised for meat, meat itself is a luxury. A child of a poor family is unlikely to have meat in his or her diet, and without the mother's milk the child is left virtually without sources of protein. This situation may have informed the choice of the word *kwashiorkor* to describe this condition. Derived from the Ga language of coastal Ghana in Africa, the word is based on *kwàsìokó,* a Ga term for "the influence a child is said to be under when a second child comes." In regions where birth control is unavailable or simply is not used, it is easy to imagine how an older child would be forced to give up the mother's milk to make room for a second child.

The results are devastating for the child deprived of protein sources. The most shocking outward manifestation of the condition is, of course, the swollen, bloated abdomen, brought about by a decrease in the amounts of the protein albumin (also found in egg whites) in the bloodstream. Skin discoloration may occur, along with severe diarrhea, an enlarged liver, and atrophy, or withering, of muscles and glands. Kwashiorkor can bring about retarded mental and physical development as well, but at least there is a treatment: adding proteins to the diet. For this reason, aid organizations supply powdered milk, which, if administered to these undernourished children in time, can save them from further damage to their bodies and minds.

MALNUTRITION IN THE UNITED STATES. Malnutrition exists even in the United States and not only in the form of overnourishment. Particularly among the nation's poor, undernourishment is serious, though it is not necessarily because food is unavailable to poor families. Rather, the right food may be unavailable, because the health foods described at the conclusion of this essay tend to be expensive. Furthermore, lack of education and information ensures that poor families maintain destructive dietary practices that leave their bodies deprived of essential nutrients. Low-cost, high-bulk items, such as sugar, white flour, and corn meal, may provide immediate satisfaction to the stomach, but they leave the body undernourished in the long run.

Nevertheless, the most prevalent form of malnutrition in America is still overnourishment. Implied in the term *overnourishment,* of course, is the idea that the person so afflicted is not eating the right kinds of things, because it is hard to be overnourished with a proper diet. Junk foods, such as one finds in the candy aisle of a convenience store or in a fast-food restaurant, contain carbohydrates and some proteins (not to mention *plenty* of fats); usually, these nutrients are presented in such a way as to maximize taste and minimize nutritional value. The result is "empty calories" that simply go to the waistline, buttocks, and abdomen of the consumer.

America is awash in food, but very little of it is the kind of food that sustains the health of the body or prolongs life. People have been conditioned by advertising to believe that white bread is the only kind of bread (even though the process of refining white flour leaches out most of the nutrients); that it is possible to have "zero

fat" cookies sweetened with white sugar (which simply turns to fat as soon as the body digests it); and that a diet of burgers, fries, and soft drinks is "normal." The result is an overnourished, overweight populace whose life spans are being cut short.

There is another way, however, as a visit to a well-stocked health-food grocery store (or even the organic/health food section of a mainstream grocery store) will illustrate. After trying genuine whole wheat or sprouted wheat instead of white bread, fructose or cane-juice sweeteners in place of refined sugar, free-range chicken and grass-fed beef rather than meats pumped full of chemicals, many Americans might be surprised to learn just how good food can taste—and how good they can feel.

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VITAMINS

CONCEPT

Most of us have been told to take our vitamins, but few people know why, and despite all the talk about them in modern culture, vitamins remain something of a mystery. Vitamins are organic substances, essential for maintaining life functions and preventing disease among humans and animals and even some plants. They are found in very small quantities in food; certain health specialists recommend taking vitamin supplements to augment the supplies in food, while others insist that a well-balanced diet provides all the vitamins that an ordinary person needs. Some vitamins, such as vitamin C and the B complex, are water-soluble, which means that they are excreted easily and must be ingested every day. Others, such as vitamins A, D, E, and K, are fat-soluble and therefore are retained in the body's fatty tissues. With such vitamins, there may be a danger of taking too much, but in the case of most vitamins, the greatest harm comes from not receiving enough. Vitamin deficiencies can be the cause of rickets, pellagra, and other diseases that have plagued the poor in the Western world and the third world in the past and in the present.

HOW IT WORKS

An Introduction to Vitamins

Once they were called *vitamines,* but for reasons that we address later, the "e" was dropped, and they became known as *vitamins.* There is also a reason for the strange alphabet of vitamins (A, B, C, D, E, K), which, like the change in spelling, came out of the early days of scientific research into the subject during the first third of the twentieth century. Though people did not know about vitamins per se until that time, folk wisdom certainly had taken account of the fact that certain foods are essential to the health and well-being of humans and animals.

Vitamins may be defined as organic substances, found in food, that are essential in very small quantities for the health of most animals and some plants. Organic substances, discussed in The Biosphere, are compounds (substances in which atoms of more than one element are chemically bonded to one another) containing hydrogen and carbon. Primarily, vitamins work with enzymes (protein materials that speed up chemical reactions in the bodies of plants and animals) in regulating metabolic processes—that is, processes that convert food to energy. They do not in themselves provide energy, however, and thus vitamins alone do not qualify as a form of nutrition.

Organisms require vitamins only in very small amounts: the total amount of vitamin mass a person needs in one day, for instance, is only about 0.0011 lb. (0.5 g). Yet vitamins are absolutely essential to the maintenance of health and for disease prevention, and most animals are not capable of synthesizing or manufacturing vitamins on their own. Nonetheless, most animals can produce vitamin C, though there are exceptions—humans included.

Animals depend on plants for their nutrition, either directly or indirectly (i.e., either by consuming the plant or by consuming an animal that has consumed the plant). Plants, on the other hand, are autotrophs, meaning that they can meet their nutritional needs with only sunlight, water, and a few chemical compounds. Among the nutrients plants produce are vita-

mins, which they pass on to animals that consume them directly or indirectly. (See Food Webs for more about autotrophs and the relationship of animal consumers to them.)

CLASSIFYING VITAMINS

Numerous vitamin groups are necessary for the nutritional needs of humans, and though only minute amounts of each are required to achieve their purpose, without them life could not be maintained. Some vitamins, including A, D, E, and K, are fat-soluble, meaning that they are found in fattier foods and in body fat. Thus, they can be stored in the body; for this reason, it is not necessary to include them in the diet every day. In fact, it could be dangerous to do so, since it is possible that they would build up to toxic levels in the tissues. Other vitamins, the most notable of which are vitamin C and the many vitamins in what is known as the "B complex," are water-soluble. They are found in the watery parts of food and body tissue, and because they are excreted regularly in the urine, they cannot be stored by the body. Instead, they must be consumed on a daily basis. This difference in solubility is extremely important to the way the vitamins function within an organism and in the ways and amounts in which they are consumed.

THE NAMES OF VITAMINS. Vitamins originally were classified in terms of their solubility in water or in fat, and these distinctions remain important for the reasons outlined above. Today, vitamins are known primarily by letters of the alphabet, a fact that harks back to a naming system developed as more and more vitamins were discovered in the early years of the twentieth century.

As scientists detected the existence of more vitamins, or what they thought were vitamins, they assigned to them successive letters of the alphabet: A, B, C, and so on. Eventually, however, they discovered that some substances originally thought to be vitamins were not vitamins, and they removed them from the roster. For example, what used to be called vitamin F is simply an essential fatty acid, a necessary component of the diet of a mammal but not the same thing as a vitamin. In other cases, what were once believed to be individual vitamins later were subsumed into the B complex. Among these substances are riboflavin, formerly termed vitamin G, and biotin, once called vitamin H. The result is that today the only alphabetical vitamin names are A, the B complex, C, D, E, and K.

REAL-LIFE APPLICATIONS

FAT-SOLUBLE VITAMINS

We are accustomed in modern life to being told that fat is bad for us, but to quote a much-cited line from the American composer George Gershwin's opera *Porgy and Bess,* "It ain't necessarily so." Fat is not inherently bad for people; in fact, a certain amount in the diet is essential. The problem in America today is the type of fat that people consume. There is a big difference between the healthy, natural, unsaturated fats one might find, say, in fresh salmon, and the highly processed and saturated fats in a bag of potato chips. (The term *saturated* means that every gap in which a hydrogen atom could fit in a string of carbon and hydrogen atoms has been filled. This helps make fats firm, for use in such products as shortening.)

Such fat is extremely harmful, because the body is not able to process it; even so, a certain amount of natural fat in the diet can be highly beneficial. This is true in large part because fat can serve as a medium for the fat-soluble vitamins A, D, E, and K, which are deposited in the body's fat cells. But as we noted earlier, it is important not to overdose on fat-soluble vitamins, because then what is inherently healthy can become extremely unhealthy.

VITAMIN A. In 1596 the Dutch explorer Willem Barents (1550–1597) and his shipwrecked crew spent a grueling winter on the island of Novaya Zemlya in the Arctic Ocean north of Russia. They had sailed from Holland in search of the Northeast Passage, which, like the more famous Northwest Passage above Canada, offered the prospect of a short, relatively direct sea route from Europe to Asia and the Americas. The problem was that the ice made sailing the northern seas virtually impossible. It would be almost three centuries before a crew managed to negotiate the Northeast Passage, by which time the European powers had long since given up all hopes of using it as a viable sailing route. (The same was true of the Northwest Passage, which was not traversed until 1906.)



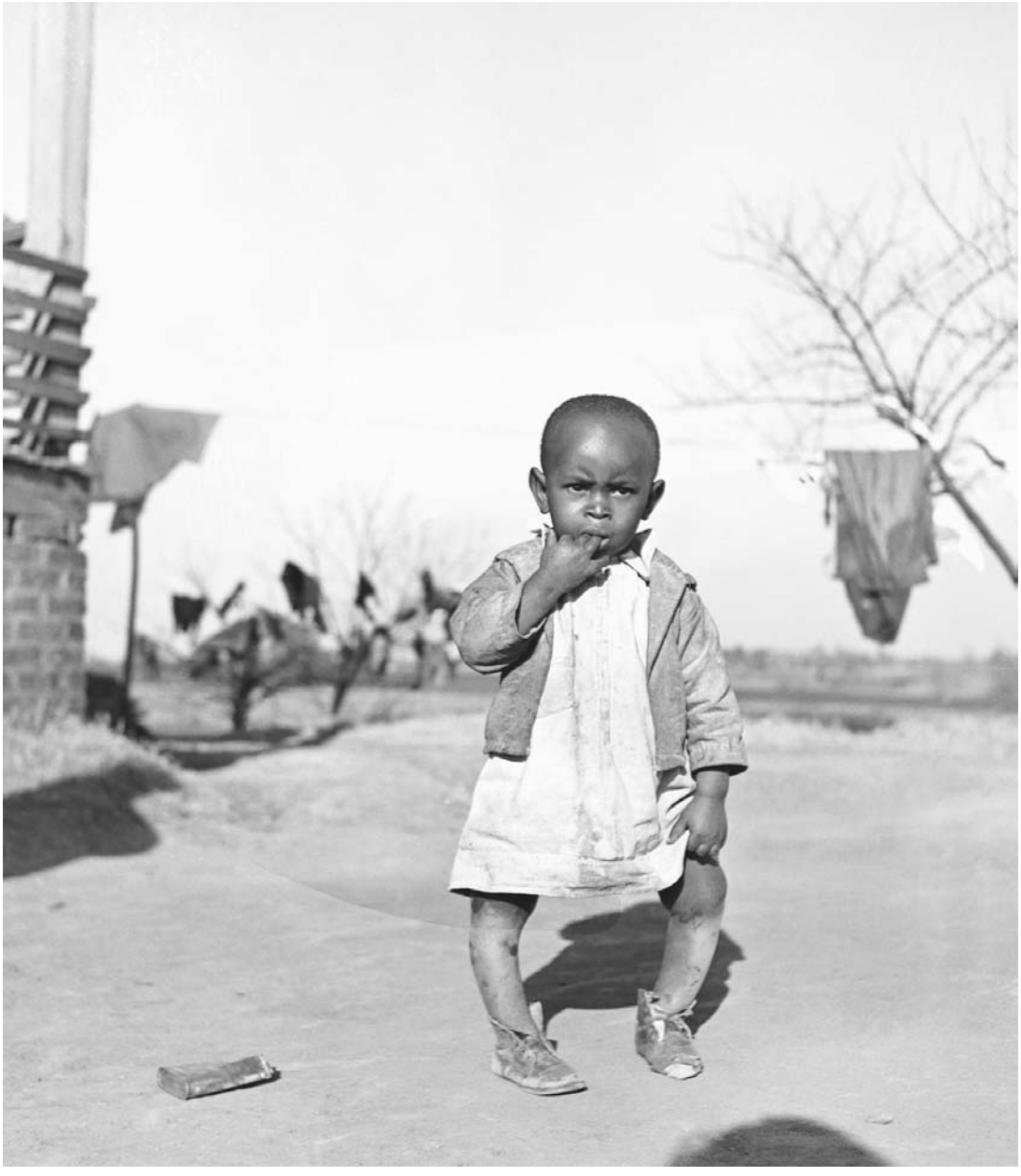
THE DUTCH EXPLORER WILLEM BARENTS AND HIS SHIPWRECKED CREW EXPERIENCED VITAMIN A POISONING WHEN THEY ATE POLAR BEARS TO STAY ALIVE ON THE ISLAND OF NOVAYA ZEMLYA IN THE ARCTIC OCEAN. POLAR BEAR LIVER CONTAINS ABOUT 450 TIMES THE RECOMMENDED DAILY DOSE OF VITAMIN A; SYMPTOMS OF POISONING INCLUDE PAINFUL JOINTS, BONE THICKENING, PEELING OF THE SKIN, AND LIVER DISEASE. *(© Bettmann/Corbis. Reproduced by permission.)*

Barents and his men knew none of that, nor would they have cared in that miserable winter of 1596–1597. All they cared about was survival, the chances for which seemed slim—and not just because of the almost inhuman cold or the fact that their ship had been cracked to pieces by the ice. Men were dying of scurvy, a vitamin-deficiency disease we discuss later in the context of vitamin C, as well as from the cold. Yet there were a few blessings, mainly in the form of available wood for fuel and animals for food. The men killed polar bears and ate their meat, and no doubt they were thankful just to stay alive. They could not have guessed, however, that they were actually killing themselves with an overdose of vitamin A.

Just 1 lb. (0.454 kg) of polar bear liver contains about 450 times the recommended daily dose of vitamin A, and the men in Barents's expedition were absorbing far more of the vitamin than they should have. In time, they began to experience the effects of vitamin A poisoning: painful joints, bone thickening, peeling of the skin over the entire body, and chronic liver disease. When spring came, the men managed to make it off the island, but many of them—Barents included—never lived to see Holland again, in part because the side effects of vitamin A toxicity had weakened them.

So why take vitamin A at all? Because it is necessary for proper growth of bones and teeth, for the maintenance and functioning of skin and mucous membranes, and for the ability to see in dim light. There is some evidence that it can help prevent cataracts (a clouding of the lens in the eye) and cardiovascular disease, a condition of the heart and circulatory system. Furthermore, when taken at the onset of a cold, vitamin A can ward off the illness and fight its symptoms.

One of the first signs of vitamin A deficiency is "night blindness," in which the rods of the eye (necessary for night vision) fail to function normally. Extreme cases of vitamin A deficiency can lead to total blindness. Other symptoms include dry and scaly skin, problems with the mucous linings of the digestive tract and urinary system, and abnormal growth of teeth and bones. The bodies of healthy adults who have an adequate diet can store several years' supply of this vitamin, but young children, who have not had time to build up such a large reserve, suffer from



During the Great Depression, a child in the southern United States shows signs of rickets, stemming from vitamin D deficiency. Under the influence of this debilitating and disfiguring disease, the legs become bowed by the weight of the body, and the wrists and ankles thicken. *(© Marion Post Wolcott/Corbis. Reproduced by permission.)*

deprivation much more quickly if they do not consume enough.

Vitamin A is present in meats (mainly liver), fish oil, egg yolks, butter, and cheese. Although plants do not have vitamin A, dark green leafy vegetables and yellow fruits and vegetables (e.g., carrots, sweet potatoes, cantaloupe, corn, and peaches) contain a substance called beta-carotene, which is converted to vitamin A in the intestine and then absorbed by the body. It is nearly impossible to ingest beta-carotene in toxic amounts, unlike vitamin A from animal sources, since the body will not convert excess amounts to toxic levels of vitamin A.

VITAMIN D. Vitamin D is actually two different substances, D_2 and D_3. (There was no D_1, since the substance designated thus at one time turned out to be a mixture of several compounds, including calciferol, or D_2) Both forms of vitamin D are activated, or made effective, by

sunlight, and for this reason vitamin D often is called the *sunshine vitamin.* It is hard to suffer a vitamin D deficiency if one gets enough sunshine in combination with consuming such foods as eggs (specifically, the yolk), such fatty fish as salmon, and enriched milk. (Milk does not naturally contain vitamin D, but the vitamin is sometimes included as an additive.)

Vitamin D lets the body utilize calcium and phosphorus in bone and tooth formation, and a deficiency causes a bone disease called rickets. Under the influence of this physically debilitating and disfiguring disease, legs become bowed by the weight of the body, and the wrists and ankles thicken. The teeth are badly affected and, for a young child, take much longer to mature. Infants and children are most likely to suffer the effects of rickets, but since all milk and infant formulas have vitamin D added to them, the condition is seen rarely in the industrialized world today. In the brutal early days of the Industrial Revolution, however (i.e., in England *ca.* 1760–1830), crowded slum conditions in areas where there was little or no sunlight made possible many cases of rickets.

Whereas rickets primarily affects children, adults may suffer from a disease called osteomalacia, caused by a deficiency of vitamin D, calcium, and phosphorous. Sometimes seen in the Middle East and other parts of Asia, osteomalacia brings with it rheumatic pain and causes the bones to become soft and deformed. As with rickets, the treatment for osteomalacia is a combination of calcium, phosphorous, and vitamin D. On the other hand, as with all fat-soluble vitamins, a person may take in excessive amounts of vitamin D, which has its own ill effects: nausea, diarrhea, weight loss, and pain in the bones and joints. Damage to the kidneys and blood vessels also can occur as calcium deposits build up in these tissues.

VITAMIN E. Composed of at least seven similar chemicals called the tocopherols, vitamin E is found in green leafy vegetables, wheat germ and other plant oils, egg yolks, and meat. The main function of this vitamin is to act as an antioxidant, to counteract the harmful effects oxygen can have on tissues. It may seem strange to speak of oxygen causing harm, since it is essential to life, but oxidation is an extremely powerful chemical reaction that, under various conditions, can manifest as rotting or putrefaction, rusting, or even combustion and explosion. When an apple turns brown a few minutes after you have cut it open, it is the result of oxidation.

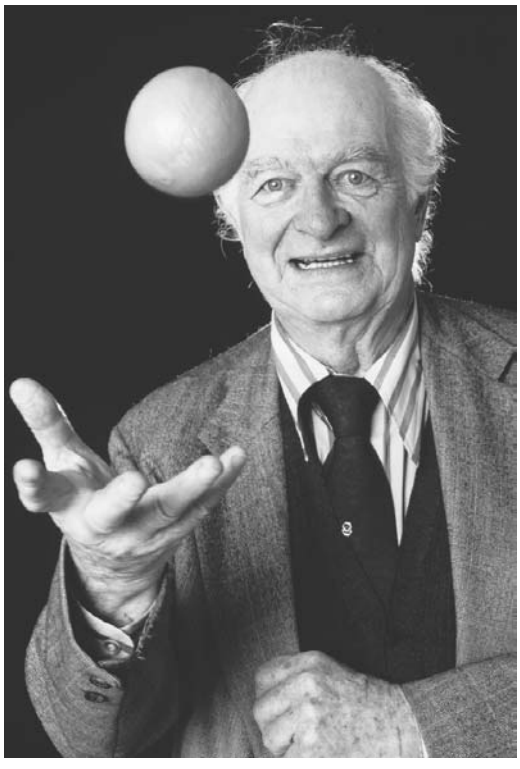
Oxidation also may be linked to the effects of aging in humans as well as to other conditions, such as cancer, hardening of the arteries, and rheumatoid arthritis. It appears that oxygen molecules, which draw electrons to them, extract these electrons from the membranes in human cells. Over time, this can cause a gradual breakdown in the body's immune system. Antioxidants, such as vitamin E or beta carotene, therefore may be important in preserving human health and well-being.

Vitamin E is particularly important for counteracting oxidation in fats. When they are oxidized, fats form a highly reactive substance called peroxide, which is often very damaging to cells. Vitamin E is more reactive (i.e., more likely to form or break chemical bonds) than the fatty acid molecule, and, therefore, the vitamin reacts instead of the fat. Because cell membranes are composed partly of fat molecules, vitamin E is vitally important in maintaining the nervous, circulatory, and reproductive systems and in protecting the kidneys, lungs, and liver.

Because vitamin E is so common in foods, it is very difficult to suffer from a deficiency of this vitamin unless a person avoids consuming fats altogether—another example of why a no-fat diet is not a healthy one. The effects of vitamin E deficiency, all of which are apparently linked to the loss of its antioxidant protection, include cramping in the legs, fibrocystic breast disease (a condition that involves the formation of lumps and cysts in the breasts), and even muscular dystrophy. The seriousness of the latter two diseases only serves to highlight the importance of vitamin E to the body.

VITAMIN K. Like vitamin D, vitamin K is composed of two groups of compounds, vitamins K_1 and K_2. There is also a substance called K_3, but this vitamin is actually menadione, a synthetic compound from which the other forms of K are derived. You can find vitamin K in many plants, especially green leafy ones such as spinach, and in liver. Vitamin K is also made by the bacteria that live in the intestine—the "good" bacteria that help make possible the processing of food through the body.

Vitamin K appears to be critical to blood clotting, thanks to its role in assisting the formation of a chemical called prothrombin in the liver.



THE AMERICAN CHEMIST LINUS PAULING (SHOWN TOSSING AN ORANGE), WINNER OF THE NOBEL PRIZES IN CHEMISTRY AND IN PEACE, HELPED POPULARIZE VITAMIN C, ALSO KNOWN AS ASCORBIC ACID. *(© Roger Ressmeyer/ Corbis. Reproduced by permission.)*

Deficiencies of this vitamin rarely occur as the result of an incomplete diet; instead, it is usually a consequence of liver damage and the blood's inability to process the vitamin. The deficiency manifests in unusual bleeding or large bruises under the skin or in the muscles. Adults in the West seldom experience vitamin K deficiencies, but newborn infants have been known to suffer from brain hemorrhage owing to a lack of this vitamin.

WATER-SOLUBLE VITAMINS

B VITAMINS. The two water-soluble vitamins, as we shall see, have played a major part in medical history. Actually, there are more than two water-soluble vitamins, because vitamin B is really a complex of about a dozen vitamins—hence, the name *B complex.* Among them are vitamin B_1 (thiamine), vitamin B_2 (riboflavin), vitamin B_6 (pyridoxine), and vitamin B_{12} (cobalamin). A few others—for example, niacin (vitamin B_7) and pantothenic acid (vitamin B_3), are known better by names other than their "B names," while biotin and folate, or folic acid, are not known by "B names" at all.

Vitamin B_1, present in whole grains, nuts, legumes (e.g., peas), pork, and liver, helps the body release energy from carbohydrates. More than 4,000 years ago, the Chinese described a disease we know today as beriberi, which affects the nervous and gastrointestinal systems and causes nausea, fatigue, and mental confusion. The cause of beriberi is a deficiency of thiamine, or B_1, found in the husks or bran of rice and grains. White rice, which most people find more pleasing to the palate than brown rice, is the result of a milling and polishing process in which the husks—and along with them, this important nutrient—are removed. Manufacturers today produce "enriched" rice, flour, and other grain products by adding thiamine back in, but until scientists discovered the importance of thiamin in grain husks, many people, especially in the Far East, suffered the effects of beriberi. (Early research on beriberi will be discussed later.)

Vitamin B_2 helps the body release energy from fats, proteins, and carbohydrates. It can be obtained from whole grains, organ meats (e.g., liver), and green leafy vegetables. Lack of this vitamin causes severe skin problems. Vitamin B_6 is important in the building of body tissue as well as in protein metabolism and the synthesis of hemoglobin (an iron-containing pigment in red blood cells that is responsible for transporting oxygen to the tissues and removing carbon dioxide). A deficiency can cause depression, nausea, and vomiting. Vitamin B_{12} is necessary for the proper functioning of the nervous system and in the formation of red blood cells. It can be obtained from meat, fish, and dairy products. Anemia (a lack of red blood cells, which produces a lethargic condition), nervousness, fatigue, and even brain degeneration, can result from vitamin B_{12} deficiency.

Niacin is also highly important to human health, as we explain later in the context of the disease pellagra. Pantothenic acid helps release energy from fats and carbohydrates and is found in large quantities in egg yolks, liver, eggs, nuts, and whole grains. Deficiency of this vitamin causes anemia. Biotin, widely available from grains, legumes, and liver, plays a part in the release of energy from carbohydrates and in the formation of fatty acids. A lack of biotin causes dermatitis, or skin inflammation.

VITAMIN C. The American chemist and peace activist Linus Pauling (1901–1994), winner of the Nobel Prize in chemistry (1954) and peace (1962), helped popularize vitamin C, also known as *ascorbic acid.* It was Pauling who originated the idea, now widespread in society, that massive doses of vitamin C can ward off the common cold. Pauling went further, by maintaining that vitamin C offers protection against some forms of cancer. While scientific studies have been unable to prove this theory, they do suggest that the vitamin can at least reduce the severity of the symptoms associated with colds.

Most animals can synthesize this vitamin in the liver, where glucose (a type of sugar that occurs widely in nature) is converted to ascorbic acid. This is not the case with at least four types of animal: monkeys, guinea pigs, Indian fruit bats, and humans, all of which must obtain vitamin C from their diets. Citrus fruits, berries, and some vegetables (e.g., tomatoes and peppers) are good sources of vitamin C. It is a fragile vitamin, one that is oxidized or destroyed easily. Food storage or food processing can render it ineffective; so, too, can soaking vitamin C–containing fruits and vegetables in water for long periods.

Vitamin Deficiencies and History

Most of the early history in the study of vitamins centered around what are now known as the *water-soluble vitamins.* Although vitamins as such were not discovered until early in the twentieth century, it was common knowledge long before that time that substances in certain foods were necessary for good health. An important turning point came in the mid–eighteenth century, with the work of the Scottish physician James Lind (1716–1794) on a vitamin deficiency condition that jeopardized England's vast merchant and military navies.

At a time when England had emerged as the world's leading sea power, even Her Majesty's sailing crews were at the mercy of a condition known as scurvy. Common among crews who had been at sea too long, scurvy could result in swollen joints, bleeding gums, loose teeth, and an inability to recover from wounds. Scientists today recognize scurvy as resulting from a deficiency of vitamin C, available in such citrus fruits as oranges. At the time, however, the concept of vitamins was unknown, and sailors at sea continued to live on a diet that consisted primarily of salted meats and hard biscuits—items that could be stored easily without spoilage in an era before refrigeration.

In 1746, Lind, a ship's doctor, observed that 80 of 350 seamen aboard his ship came down with scurvy during a 10-week cruise. Conducting a controlled experiment, he took 12 of the sailors in whom scurvy had developed and divided them into six groups. He gave each pair different substances, such as nutmeg, cider, seawater, and vinegar; the final pair was given lemons or oranges. The two men given the oranges and lemons both completely recovered in about a week. Not only was this a milestone in the history of vitamin research, but it also was the first example of a clinical trial, or the testing of a medication by careful and well-documented experimentation in which other variables or factors are kept unchanged.

It would be another half-century before the British navy adopted Lind's techniques. Another Scottish physician, Sir Gilbert Blane (1749–1834), had long fought for the adoption of Lind's methods, and finally, in 1796, he persuaded the navy to give each sailor a daily ration of lemons. At that time, the term lime was common for both lemons and limes, and, as a result, British sailors became known as *limeys.* Eventually, the treatment spread to the population as a whole, but outbreaks of scurvy continued until after World War I, when doctors isolated vitamin C as the controlling factor in scurvy prevention.

BERIBERI IN THE DUTCH EAST INDIES. In 1897 the Dutch government sent the physician Christiaan Eijkman (1858–1930) as part of a government commission to the Dutch East Indies (now Indonesia), which had been long afflicted by a condition known as beriberi. There are various forms of this disease, including infant beriberi, which can kill a breast-feeding baby after the fifth month, as well as various juvenile and adult forms. In the childhood and adult versions of the disease, there is a preliminary condition of fatigue, loss of appetite, and a numb, tingling feeling in the legs. This condition can lead to either wet beriberi, characterized by the accumulation of fluid throughout the body and a rapid heart rate that can bring about sudden death, or dry beriberi,

KEY TERMS

AMINO ACIDS: Organic compounds made of carbon, hydrogen, oxygen, nitrogen, and (in some cases) sulfur bonded in characteristic formations. Strings of amino acids make up proteins.

ANEMIA: A condition marked by a lack of red blood cells or hemoglobin or a shortage in total blood volume, any one of which can produce a lethargic condition.

ANTIOXIDANT: An enzyme, or some other organic substance, that is capable of counteracting the negative impact of oxygen (which draws electrons to it) on living tissue.

CARBOHYDRATES: Naturally occurring compounds, consisting of carbon, hydrogen, and oxygen, whose primary function in the body is to supply energy. Included in the carbohydrate group are sugars, starches, cellulose, and various other substances.

COMPOUND: A substance in which atoms of more than one element are bonded chemically to one another.

ENZYME: A protein material that speeds up chemical reactions in the bodies of plants and animals.

GLUCOSE: A type of sugar that occurs widely in nature. Glucose is the form in which animals usually receive carbohydrates.

HEMOGLOBIN: An iron-containing pigment in red blood cells that is responsible for transporting oxygen to the tissues and removing carbon dioxide.

METABOLISM: The chemical process by which nutrients are broken down and converted into energy or used in the construction of new tissue or other material in the body.

MINERALS: Inorganic substances that, in a nutritional context, serve a function similar to that of vitamins. Minerals may include chemical elements, particularly metallic ones, such as calcium or iron, as well as some compounds.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to compounds containing carbon and hydrogen.

PROTEINS: Large molecules built from long chains of amino acids. Proteins serve the functions of promoting normal growth, repairing damaged tissue, contributing to the body's immune system, and making enzymes.

TISSUE: A group of cells, along with the substances that join them, that form part of the structural materials in plants or animals.

VITAMINS: Organic substances that, in extremely small quantities, are essential to the nutrition of most animals and some plants. In particular, vitamins work with enzymes in regulating metabolic processes; however, they do not in themselves provide energy, and thus vitamins alone do not qualify as a form of nutrition.

which is marked by a loss of sensation and weakness in the legs. The patient first needs to walk with the aid of a stick and then becomes bedridden and easy prey to infectious diseases.

Experimenting with birds, Eijkman noticed that some of the fowl experienced paralysis and polyneuritis (a disorder affecting several nerves at once), as in the dry form of beriberi. The director

of the hospital had told Eijkman that he could not feed the birds with table scraps from the dining hall, where the diet was heavy in polished rice. The doctor thus was forced to feed his birds whole rice, and something amazing happened: the birds began to regain their ability to move and experienced no recurrence of paralysis.

Eijkman's colleagues rejected his claim that the birds had contracted some form of beriberi, though, in fact, he was correct. He was incorrect, however, in his supposition that the polished rice contained a toxin that was missing from the whole, unpolished rice. After Eijkman and the rest of the medical commission left the East Indies, another Dutch physician, Gerrit Grijns (1865–1944), stayed on to study the disease. He discovered that when the chickens were taken off the rice diet completely and fed meat instead, they did not show signs of the characteristic paralysis; if the meat was overcooked, however, the condition reappeared. In 1901, Grijns showed that beriberi could be cured by putting the rice polishings back into the rice. As it turned out, the husks and the meat contained vitamin B_1, also present in wheat germ, whole grain and enriched bread, legumes, peanuts, and nuts.

PELLAGRA IN THE AMERICAS. A vitamin-deficiency disease often associated with poverty, pellagra produces symptoms known as the "three Ds": diarrhea, dermatitis, and dementia, or mental deterioration. It was first identified in 1762 by the Spanish physician Gaspar Casal (*ca.* 1680–1759), who wrote about the "mal de la rosa"—so called because of the reddened dermatitis that appeared around the back of the victim's neck—that afflicted sufferers in one particular region of Spain.

Casal was far ahead of his time in maintaining that inadequate nutrition caused pellagra, but for many centuries the belief persisted that the disease resulted from infection. The breakthrough came with the work of the American physician Joseph Goldberger (1874–1929), a member of the U.S. Public Health Service who studied the high numbers of pellagra cases among poor blacks and whites in the southern United States. Goldberger established that pellagra stems from insufficient niacin, which is required to release energy from glucose.

Niacin is present in whole grains, meat, fish, and dairy products. One of the foods from which niacin is not easily available is corn, and it so happened that corn products constituted a major part of the diet in areas suffering from high rates of pellagra. The poor of Spain and Latin America subsisted on a diet heavy in corn products, such as tortillas and polenta, while their counterparts in the southern United States survived on cornbread, grits, hominy, and other variants of corn. Although such foods made it possible to fill the stomach cheaply, this diet was killing people in large numbers because it was not delivering the essential B vitamin niacin.

MODERN KNOWLEDGE OF VITAMINS. As it turned out, corn, in fact, does contain niacin, but to release the niacin from the large, fibrous molecules in corn, it is necessary to treat the corn with an alkaline solution, such as limewater. This is just one example of the vast knowledge that has accumulated since the time when the Polish-American biochemist Casimir Funk (1884–1967) coined the term *vitamine* in 1912. The first half of the word came from the Latin *vita,* or "life," and the second half reflected Funk's belief that all these substances belonged to a group of chemicals known as *amines.* Scientists later dropped the "e" when they discovered that not all vitamins contain an amine group.

In the director Stephen Spielberg's acclaimed 1987 film *Empire of the Sun,* one of the characters asks another, "Do you believe in vitamins?" The question reflects the relative newness of vitamins as an idea at the time when the movie was set, during World War II. After the war, interest in commercially produced vitamin supplements exploded, particularly among America's middle classes. Pauling's promotion of vitamin C, coming in the 1950s and 1960s, found a willing audience.

Although vitamin supplements remain a big business today, opinions vary as to the importance of enhancing one's diet with them. Many nutritionists insist that eating a well-balanced diet, consisting of the major food substances, is an effective and economical way to obtain nutrients for health. On the other hand, advocates of health foods and alternative medicine (medical practices that are not recognized officially by groups of university-trained and state-licensed medical doctors) insist that the recommended daily allowances established by the U.S. Food and Drug Administration do not provide sufficient vitamins for an average person.

The American Dietetic Association (ADA) recommends that nutrient needs come from a variety of foods taken from different dietary sources rather than from self-prescribed vitamin supplements. The organization makes allowances, however, for supplement usage by people who need extra doses of key vitamins and minerals. Examples include the use of iron supplements by women experiencing heavy menstrual bleeding as well as supplements of iron, folic acid, and calcium by pregnant women.

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GENETICS

GENETICS
HEREDITY
GENETIC ENGINEERING
MUTATION

GENETICS

CONCEPT

Genetics is the area of biological study concerned with heredity and with the variations between organisms that result from it. It demands an understanding of numerous terms, such as DNA (deoxyribonucleic acid), a molecule in all cells that contains blueprints for genetic inheritance; genes, units of information about particular heritable traits, which are made from DNA; and chromosomes, DNA-containing bodies, located in the cells of most living things, that hold most of the organism's genes. The vocabulary of genetics goes far beyond these three terms, as we shall see, but these are the core concepts. Among the areas in which genetics is applied is forensic science, or the application of science to matters of law—specifically, through "DNA fingerprinting," whereby samples of skin, blood, semen, and other materials can be used to prove or disprove a suspect's innocence. Another fascinating application of genetics is the Human Genome Project, an effort whose goals include the location and identification of every gene in the human body.

HOW IT WORKS

Genetics and Heredity

Genetics and heredity, the subject of another essay in this book, are closely related ideas. Whereas heredity is the transmission of genetic characteristics from ancestor to descendant through the genes, genetics is concerned with hereditary traits passed down from one generation to the next. It is very hard, if not impossible, to separate the two concepts completely, yet the entire body of knowledge encompassed by these topics is so large and so complex that it is best to separate them as much as possible. For this reason, the Heredity essay is concerned with such issues as how traits are passed on and why they appear in a particular generation but not another. That essay addresses the topics of alleles, dominant and recessive genes, and so on. It also briefly discusses the history of studies in areas that encompass genetics, heredity, and the mechanics thereof. In general, the Heredity essay is concerned with the larger patterns of inheritance over the generations, while the present one examines inheritance at a level smaller than the microscopic—that is, from the molecular or biochemical level.

Somatic and Germ Cells

Heredity begins with the cell, the smallest basic unit of all life. The information for heredity is carried within the cell nucleus, which is the control center not only in physical terms (it is usually located near the middle of the cell) but also because it contains the chromosomes. Within these threadlike structures is the genetic information organized in DNA molecules.

There are two basic types of cell in a multicellular organism: somatic, or body, cells, and germ, or reproductive, cells. The somatic cells are the primary components of most organisms, making up everything except some of the the cells in reproductive organs. The somatic cells of humans have 23 pairs of chromosomes, or 46 chromosomes overall, and are thus known as diploid cells. As the cells grow, they reproduce themselves by a process called *mitosis,* whereby a diploid cell splits to produce new diploids, each of which is a replica of the original. Thus cells grow and are replaced, making possible the formation of specific tissues and organs, such as

muscles and nerves. Without mitosis, an organism's cells would not regenerate, resulting not only in cell death but possibly even the death of the entire organism. Mitosis is also the means of reproduction for organisms that reproduce asexually (see Reproduction).

A germ cell, by contrast, undergoes a process of cell division known as *meiosis,* whereby it becomes a haploid cell—a cell with half the basic number of chromosomes, which for a human would be 23 unpaired chromosomes. The sperm cells in a male and the egg cells in a female are both haploid germ cells: each contains only 23 chromosomes, and each is prepared to form a new diploid by fusion with another haploid. Sperm cells and egg cells are known as gametes, mature male or female germ cells that possess a haploid set of chromosomes and are prepared to form a new diploid by undergoing fusion with a haploid gamete of the opposite sex.

When egg and sperm fuse, they form a zygote, in which the diploid chromosome number is restored, with the zygote possessing the same chromosomes as *both* the sperm and the egg. This cell carries all the genetic information needed to grow into an embryo and eventually a full-grown human, with the specific traits and attributes passed on by the parents. Not all offspring of the same parents are the same, of course, and this is because the sperm cells and egg cells vary in their genetic codes—that is, in their DNA blueprints.

The DNA Blueprint

To understand genes and their biological function in heredity, it is necessary to understand the chemical makeup and structure of DNA. The complete DNA molecule often is referred to as the *blueprint for life,* because it carries all the instructions, in the form of genes, for the growth and functioning of organisms. This fundamental molecule is similar in appearance to a spiral staircase, which also is called a double helix. The sides of the DNA ladder are made up of alternate sugar and phosphate molecules, like links in a chain. The rungs, or steps, of DNA are made from a combination of four different chemical bases. Two of these, adenine and guanine, are known as purines, and the other two, cytosine and thymine, are pyrimidines. The four letters designating these bases—A, G, C, and T—are the alphabet of the genetic code, and each rung of the DNA molecule is made up of a combination of two of these letters.

DNA SEQUENCES. In this genetic code A always combines with T and C with G, to form what is called a base pair. Specific sequences of these base pairs make up the genes. Although a four-letter alphabet may seem rather small for constructing the extensive vocabulary that defines the myriad life-forms on Earth, in practice, the sequences of these base pairs make for almost limitless combinations. For any sequence, there are four possibilities as to the first two letters (AT, TA, CG, or GC) and four more possibilities for the second two letters. Thus, just for a four-letter sequence, there are 16 possibilities, and for each pair of letters added to the sequence, the total is multiplied by four. Given the long strings of base pairs that form DNA sequences, the numbers can be extremely large.

The more complex an organism, from bacteria to humans, the more rungs, or genetic sequences, appear on the ladder. The entire genetic makeup of a human, for example, may contain three billion base pairs, with the average gene unit being 2,000-200,000 base pairs long. Each one of these combinations has a different meaning, providing the code not only for the type of organism but also for specific traits, such as brown hair and blue eyes, dimples, detached earlobes, and so on and on. Except for identical twins, no two humans have exactly the same genetic information.

DNA Replication, Protein Synthesis, and RNA

Genetic information is duplicated during the process of DNA replication, which is initiated by proteins in the cells. To produce identical genetic information during cell mitosis, the DNA hydrogen bonds between the two strands arebroken, splitting the DNA in half lengthwise. This process begins a few hours before the initiation of cell mitosis, and once it is completed, each half of the DNA ladder is capable of forming a new DNA molecule with an identical genetic code. It can do this because of specific chemical catalysts (a substance that enables a chemical reaction without taking part in it) that help synthesize the complementary strand.

Catalysts formed from proteins are known as enzymes, and the functioning of specific cells and organisms is conducted by enzymes synthe-

sized by the cells. Cells contain hundreds of different proteins, complex molecules that make up more than half of all solid body tissues and control most biological processes within and among these tissues. A cell functions in accordance with the particular protein—one of thousands of different types—it contains. It is the genetic base-pair sequence in DNA that determines, or "codes for," the specific arrangement of amino acids to build particular proteins.

Since the sites of protein production lie outside the cell nucleus, coded messages pass from the DNA in the nucleus to the cytoplasm, the material inside the cell that is external to the nucleus. This transfer of messages is achieved by RNA, or ribonucleic acid, and specifically by messenger RNA, or mRNA. Other types of RNA molecules are involved in linking the amino-acids together in a sequence form to shape the protein. (For more about amino acids, proteins, and enzymes, see the respective essays devoted to each subject.)

MUTATION

Once a protein has been created for a specific function, it cannot be changed. This is why the theory of acquired characteristics (the idea that changes in an organism's overall anatomy, as opposed to changes in its DNA, can be passed on to offspring) is a fallacy. People may have genes that make it easier for them to acquire certain traits, such as larger muscles or the ability to play the piano through exercise or practice, respectively, but the traits themselves, if they are acquired during the life of the individual and are not encoded in the DNA, are not heritable.

There is only one way in which changes that take place during the life of an organism can be passed on to its offspring, and that is if those changes are encoded in the organism's DNA. This is known as *mutation.* Suppose lung cancer develops in a man as a result of smoking; unless a tendency to cancer is already a part of his genetic makeup, he cannot genetically pass the disease on to his unborn children. But if the tobacco has acted as a mutagen, a substance that brings about mutation, it is possible that his DNA can be altered in such a way as to pass on either the tendency toward lung cancer or some other characteristic.

Because DNA is extremely stable chemically, it rarely mutates, or experiences an alteration in its physical structure, during replication. But because there are so many strands of DNA in the world, and so much material in the strands, mutation is bound to happen eventually—and, to an extent, at least, this is a good thing. Mutation is the engine that drives evolution, and a certain amount of genetic variation is necessary if species are to adapt by natural selection to a changing environment. If it were not for mutation, neither humans nor the many millions of other species that exist would ever have appeared.

Mutation often occurs when chromosome segments from two parents physically exchange places with each other during the process of meiosis. This is known as *genetic recombination.* Genes also can change by mutations in the DNA molecule, which take place when a mutagen alters the chemical or physical makeup of DNA. The mutations that result are of two types, corresponding to the two basic varieties of cell: somatic mutations, which occur solely within the affected individual, and germinal mutations, which happen in the DNA of germ cells, producing altered genes that may be passed on to the next generation.

The odd thing about mutations is that while most of them are harmful, the few that are beneficial are, as we have noted, the driving force behind the evolution of life-forms that successfully adapt to their environments. Thus, while most germinal mutations bring about congenital disorders (birth defects) ranging from physical abnormalities to deficiencies in body or mind to diseases, every once in a while a germinal mutation results in an improvement, such as a change in body coloring that acts as camouflage. If the trait improves an individual organism's chances for survival within a particular environment, it may become a permanent trait of the species, because the offspring with this gene have a greater chance of survival and thus will pass on the trait to succeeding generations. (For more about mutation, see the essay by that title. See also Evolution for a discussion of the role played by mutation and natural selection in the evolution of species.)

REAL-LIFE APPLICATIONS

THE GENETICS REVOLUTION

In the modern world genetics plays a part in more dramatic breakthroughs than any other



A scientist studies the arrangement of chromosome pairs, the threadlike DNA-containing bodies in cells that carry genetic information. The Human Genome Project is working to complete a map outlining the location and function of the genes in human cells. *(© BSIP/V & L /Photo Researchers. Reproduced by permission.)*

field of biological study. These breakthroughs have an impact in a wide variety of areas, from curing diseases to growing better vegetables to catching criminals. The field of genetics is in the midst of a revolution, and at the center of this exciting (and, to some minds, terrifying) phenomenon is the realm of genetic engineering: the alteration of genetic material by direct interven-

tion in genetic processes. In agriculture, for instance, genes are transplanted from one organism to another to produce what are known as *transgenic* animals or plants. This approach has been used to reduce the amount of fat in cattle raised for meat or to increase proteins in the milk produced by dairy cattle. Fruits and vegetables also have been genetically engineered so that they do not bruise easily or have a longer shelf life.

Not all of the work in genetics is genetic engineering per se; in the realm of law, for instance, the most important application of genetics is genetic fingerprinting. A genetic fingerprint is a sample of a person's DNA that is detailed enough to distinguish it from the DNA of all others. The genetic fingerprint can be used to identify whether a man is the father of a particular child (i.e., to determine paternity), and it can be applied in the solving of crimes. If biological samples can be obtained from a crime scene—for example, skin under the fingernails of a murder victim, presumably the result of fighting against the assailant in the last few moments of life—it is possible to determine with a high degree of accuracy whether that sample came from a particular suspect. The use of DNA in forensic science is discussed near the conclusion of this essay.

THE REVOLUTION IN MEDICINE. Some of the biggest strides in genetic engineering and related fields are taking place, not surprisingly, in the realm of medicine. Genetic engineering in the area of health is aimed at understanding the causes of disease and developing treatments for them: for example, recombinant DNA (a DNA sequence from one species that is combined with the DNA of another species) is being used to develop antibiotics, hormones, and other disease-preventing agents. Vaccines also have been genetically re-engineered to trigger an immune response that will protect against specific diseases. One approach is to remove genetic material from a diseased organism, thus making the material weaker and initiating an immune response without causing the disease. (See Immunity and Immunology for more about how vaccines work.)

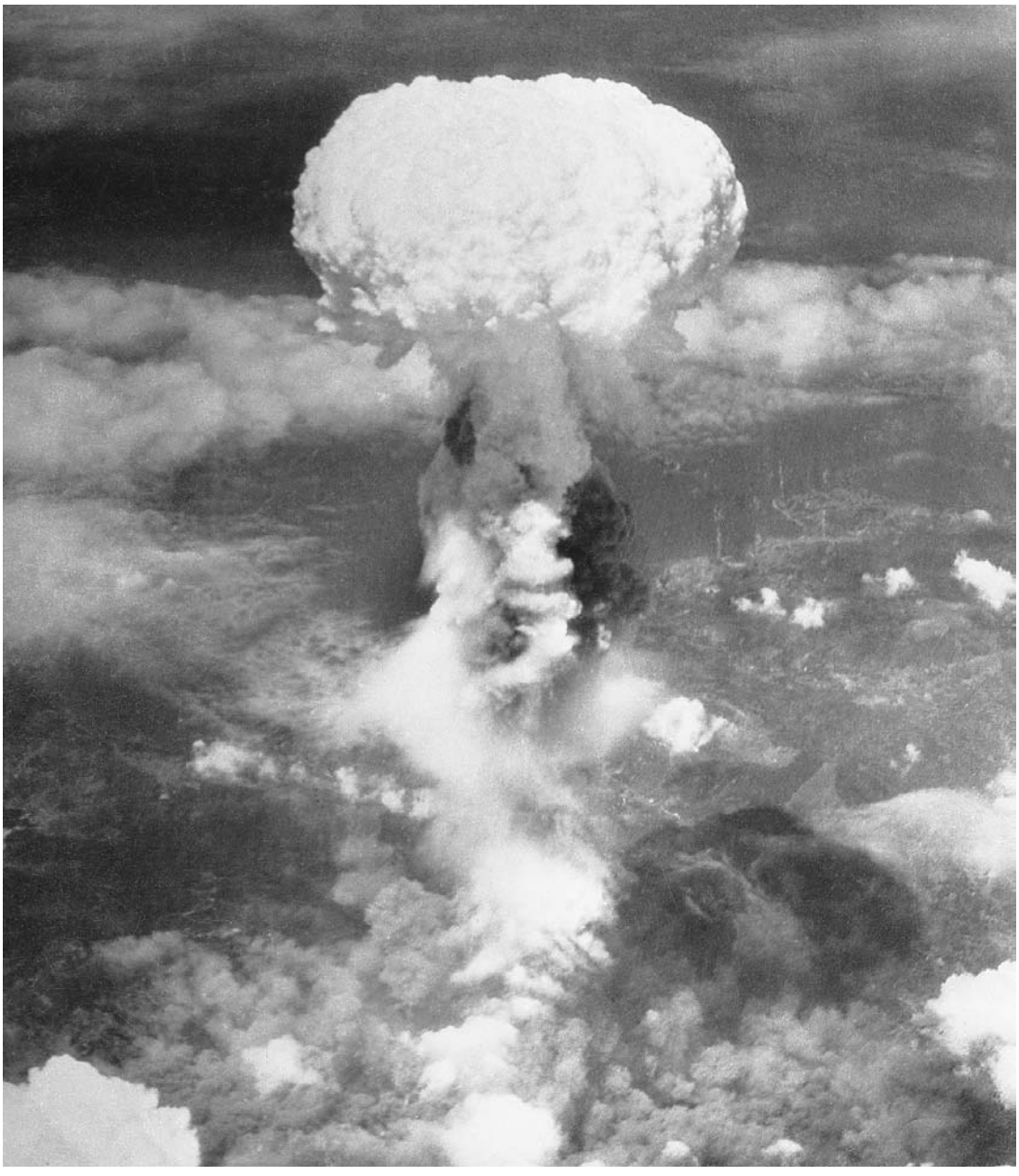
Gene therapy is another outgrowth of genetics. The idea behind gene therapy is to introduce specific genes into the body either to correct a genetic defect or to enhance the body's capabilities to fight off disease and repair itself. Since many inherited or genetic diseases are caused by the lack of an enzyme or protein, scientists hope one day to treat the unborn child by inserting genes to provide the missing enzyme. (For more about inherited disorders, see the essays Disease, Noninfectious Diseases, and Mutation.)

THE HUMAN GENOME PROJECT. One of the most exciting developments in genetics is the initiation of the Human Genome Project, designed to provide a complete genetic map outlining the location and function of the 40,000 or so genes that are found in human cells. (A genome is all of the genetic material in the chromosomes of a particular organism.) With the completion of this map, genetic researchers will have easy access to specific genes, to study how the human body works and to develop therapies for diseases. Gene maps for other species of animals also are being developed.

The project had its origins in the 1990s, with the efforts of the United States Department of Energy (DOE) and the National Institutes of Health (NIH). The NIH connection is probably clear enough, but the DOE's involvement at first might seem strange. What, exactly, does genetics have to do with electricity, petroleum, and other concerns of the DOE? The answer is that the DOE grew out of agencies, among them the Atomic Energy Commission (AEC), established soon after the explosion of the two atomic bombs over Japan in 1945. Even at that early date, educated nonscientists understood that the radioactive fallout produced from nuclear weaponry can act as a mutagen; therefore, Congress instructed the AEC to undertake a broad study of genetics and mutation and the possible consequences of exposure to radiation and the chemical by-products of energy production.

Eventually, scientists in the AEC and, later, the DOE recognized that the best way to undertake such a study was to analyze the entire scope of the human genome. The project formally commenced on October 1, 1990, and is scheduled for completion in the middle of the first decade of the twenty-first century. Upon completion, the Human Genome Project will provide a vast store of knowledge and no doubt will lead to the curing of many diseases.

Still, there are many who question the Human Genome Project in particular, and genetic engineering in general, on ethical grounds, fearing that it could give scientists or govern-



The explosion of an atomic bomb over Nagasaki, Japan, during World War II (September 1, 1945). The radioactive fallout produced from nuclear weaponry can act as a mutagen, altering the chemical or physical makeup of DNA. *(© Bettmann/Corbis. Reproduced by permission.)*

ments too much power, unleash a Nazi-style eugenics (selective breeding) program, or result in horrible errors, such as the creation of deadly new diseases. In fact, it is impossible to search "genetic engineering" on the World Wide Web without coming across the Web sites of literally dozens and dozens of agencies, activist groups, and individuals opposed to genetic engineering and the mapping of the human genome. For more about the Human Genome Project, genetic engineering, and their opponents, see Genetic Engineering.

Genetics in Forensic Science

Forensic science, as we noted earlier, is the application of science to matters of law. It is based on the idea that a criminal always leaves behind some kind of material evidence that, through careful analysis, can be used to determine the identity of the perpetrator—and to exonerate

someone falsely accused. Among those forms of material evidence of interest to forensic scientists working in the field of genetics are blood, semen, hair, saliva, and skin, all of which contain DNA that can be analyzed. In addition, there are areas of forensic science that rely on biological study, though not in the area of genetics: blood typing as well as the analysis of fingerprints or bite marks, both of which have patterns that are as unique to a single individual as DNA is.

One of the first detectives to use science, including biology and medicine, in solving crimes was a fictional character: Sherlock Holmes, whose creator, the British writer Sir Arthur Conan Doyle (1859–1930), happened to be a physician as well. The first full-fledged (and real) police practitioner of forensic science was the French police official Alphonse Bertillon (1853–1914), who developed an identification system that consisted of a photograph and 11 body measurements, including dimensions of the head, arms, legs, feet, hands, and so on, for each individual. Bertillon claimed that the likelihood of two people having the same measurements for all 11 traits was less than one in 250 million. In 1894 fingerprints, which were easier to use and more unique than body measurements, were added to the Bertillon system.

Fingerprints, unlike DNA, are unique to the individual; indeed, identical twins have the same DNA but different fingerprints. Mark Twain (1835–1910) could not have known this in 1894, when he published *The Tragedy of Pudd'nhead Wilson, and the Comedy of Those Extraordinary Twins.* Nonetheless, the story involves a murder committed by one man and blamed on his twin, who eventually is exonerated on the basis of fingerprint evidence—still a new concept at the time. In some situations, however, fingerprint evidence may be unavailable, and though law-enforcement agencies have developed extraordinary techniques for analyzing nearly invisible (i.e., latent) prints, sometimes this is still not enough.

THE SIMPSON CASE AND THE CONTROVERSY OVER DNA EVIDENCE. For example, in the infamous murder of Nicole Brown Simpson and Ron Goldman on June 12, 1994, fingerprint evidence would have been ineffective in the case against the suspect, the former football star and actor O. J. Simpson. Since Nicole Simpson was his ex-wife, the appearance of his prints at the scene of her murder in her Los Angeles home could be explained away easily, even though she had taken out a restraining order against her former husband (who she had accused of spousal abuse) some time before the murder. Rather than fingerprints, the prosecution in his murder trial used DNA evidence connecting blood at the crime scene with blood found in Simpson's vehicle. (Some of this blood was apparently his own, since he had mysterious cuts on his hands that he could not explain to police officers.)



O. J. SIMPSON REACTS TO THE JURY'S VERDICT. DESPITE DNA EVIDENCE THAT LINKED BLOOD AT THE CRIME SCENE WITH BLOOD IN HIS CAR, THE JURY FOUND HIM NOT GUILTY OF DOUBLE MURDER. *(AP/WIde World Photos. Reproduced by permission.)*

A jury found Simpson not guilty on October 3, 1995, and jurors later claimed that the prosecution had failed to make a strong case using DNA evidence. Furthermore, they cited police contamination of the DNA evidence, which had been established in their minds by Simpson's defense team, as a cause for reasonable doubt concerning Simpson's guilt. In fact, assuming that the defense was fully justified in this claim, that would have meant only that the DNA samples would have been *less* (not more) likely to convict Simpson.

KEY TERMS

ACQUIRED CHARACTERISTICS: Sometimes known as *acquired characters* or *Lamarckism,* after one of its leading proponents, the French natural philosopher Jean Baptiste de Lamarck (1744–1829), the theory of acquired characteristics is a fallacy that should not be confused with mutation. Acquired characteristics theory maintains that changes that occur in an organism's overall anatomy (as opposed to changes in its DNA) can be passed on to offspring.

AMINO ACIDS: Organic compounds made of carbon, hydrogen, oxygen, nitrogen, and (in some cases) sulfur bonded in characteristic formations. Strings of amino acids make up proteins.

BASE PAIR: A pair of chemicals that form the "rungs" on a DNA molecule, which has the shape of a spiral staircase. A base pair always consists of a type of chemical called a purine on one side and a chemical termed a pyrimidine on the other. This means that DNA base pairs always consist of adenine linked with thymine and guanine with cytosine.

BIOCHEMISTRY: The area of the biological sciences concerned with the chemical substances and processes in organisms.

BODY CELL: See *somatic cell.*

CHROMOSOME: A DNA-containing body, located in the cells of most living things, that holds most of the organism's genes.

CONGENITAL DISORDER: An abnormality of structure or function or a disease that is present at birth. Congenital disorders also are called *birth defects.*

CYTOPLASM: The material inside a cell that is external to the nucleus.

DIPLOID: A term for a cell that has the basic number of doubled chromosome cells. In humans, somatic cells, which are diploid cells, have 23 pairs of chromosomes, for a total of 46 chromosomes.

DNA: Deoxyribonucleic acid, a molecule in all cells, and many viruses, that contains genetic codes for inheritance.

DOMINANT: In genetics, a term for a trait that can manifest in the offspring when inherited from only one parent. Its opposite is *recessive.*

ENZYME: A protein material that speeds up chemical reactions in the bodies of plants and animals without itself taking part in or being consumed by those reactions.

FORENSIC SCIENCE: The application of science to matters of law and legal or police procedure.

GAMETE: A mature male or female germ cell that possesses a haploid set of chromosomes and is prepared to form a new diploid by undergoing fusion with a haploid gamete of the opposite sex.

GENE: A unit of information about a particular heritable trait. Usually stored on chromosomes, genes contain specifications for the structure of a particular polypeptide or protein.

GENETIC ENGINEERING: The alteration of genetic material by direct intervention in genetic processes.

GENETIC FINGERPRINT: A sample of a person's DNA that is detailed enough

KEY TERMS CONTINUED

to distinguish it from all other people's DNA.

GENETIC RECOMBINATION: A process whereby chromosome segments from two parents physically exchange places with each other during the process of meiosis. This is one of the ways that mutation occurs.

GENETICS: The area of biological study concerned with heredity, with hereditary traits passed down from one generation to the next through the genes, and with the variations between organisms that result from heredity.

GENOME: All of the genetic material in the chromosomes of a particular organism.

GERM CELL: One of two basic types of cells in a multicellular organism. In contrast to somatic, or body, cells, germ cells are involved in reproduction.

GERMINAL MUTATION: A mutation that occurs in the germ cells, meaning that the mutation can be passed on to the organism's offspring.

HAPLOID: A term for a cell that has half the number of chromosome cells that appear in a diploid, or somatic, cell. In humans, germ cells, which are haploid cells, have 23 unpaired chromosomes, as opposed to the 23 paired chromosomes (46 overall) that appear in a somatic cell.

HEREDITY: The transmission of genetic characteristics from ancestor to descendant through the genes.

HERITABLE: Capable of being inherited.

MEIOSIS: The process of cell division that produces haploid genetic material. Compare with *mitosis.*

MITOSIS: A process of cell division that produces diploid cells. Compare with *meiosis.*

MRNA: Messenger ribonucleic acid, a molecule of RNA that carries the genetic information for producing proteins.

MUTAGEN: A chemical or physical factor that increases the rate of mutation.

MUTATION: Alteration in the physical structure of an organism's DNA, resulting in a genetic change that can be inherited.

NATURAL SELECTION: The process whereby some organisms thrive and others perish, depending on their degree of adaptation to a particular environment.

NUCLEIC ACIDS: Acids, including DNA and RNA, that are made up of nucleotide chains.

NUCLEOTIDE: A compound formed from one of several types of sugar joined with a base of purine or pyrimidine (see *base pair*) and a phosphate group. Nucleotides are the basis for nucleic acids.

NUCLEUS: The control center of a cell, where DNA is stored.

POLYPEPTIDE: A group of between 10 and 50 amino acids.

PROTEINS: Large molecules built from long chains of 50 or more amino acids. Proteins serve the functions of promoting normal growth, repairing damaged tissue, contributing to the body's immune system, and making enzymes.

RECESSIVE: In genetics, a term for a trait that can manifest in the offspring only if it is inherited from both parents. Its opposite is *dominant.*

KEY TERMS CONTINUED

REPRODUCTIVE CELL: See *germ cell.*

RNA: Ribonucleic acid, a molecule translated from DNA in the cell nucleus that directs protein synthesis in the cytoplasm. See also *mRNA.*

SOMATIC CELL: One of two basic types of cells in a multicellular organism. In contrast to germ cells, somatic cells (also known as *body cells*) do not play a part in reproduction; rather, they make up the tissues, organs, and other parts of the organism.

SOMATIC MUTATION: A mutation that occurs in cells other than the reproductive, or sex, cells. These mutations, as contrasted with germinal mutations, cannot be transmitted to the next generation.

SYNTHESIZE: To manufacture chemically, as in the body.

TRANSLOCATION: A mutation in which chromosomes exchange parts.

ZYGOTE: A diploid cell formed by the fusion of two gametes.

At the same time, a number of legitimate concerns regarding the use of DNA evidence were raised by experts for the defense in the Simpson trial. Samples can become contaminated and thus difficult to read; small samples are difficult for analysts to work with effectively; and results are often open to interpretation. Furthermore, the outcome of the Simpson case illustrates the fact that findings based on DNA evidence are not readily understood by non-specialists, and may not make the best basis for a case-particularly in one so fraught with controversy. The prosecution based its case almost entirely on extremely technical material, explained in excruciating detail by experts who had devoted their lives to studying areas that are far beyond the understanding of the average person. Attempting to wow the jurors with science, the prosecution instead seemed to create the impression that DNA evidence was some sort of hocus-pocus invented to frame an innocent man. Simpson went free, though the jury in a 1996 civil trial (which took a much simpler approach, eschewing complicated DNA testimony) found him guilty.

DNA EVIDENCE SUCCESS STORIES. Because of the Simpson case, the use of DNA evidence gained something of a bad name. Nonetheless, it has been successful in less high profile cases, beginning in 1986, when English police tracked down a rapist and murderer by collecting blood samples from some 2,000 men. One of them, named Colin Pitchfork, paid another man to provide a sample in his place. This attracted the attention of the police, who tested his DNA and found their man.

Since that time, DNA evidence has been used in more than 24,000 cases and has aided in the conviction of about 700 suspects. The DNA in such cases is not always obtained from a human subject. In the investigation of the May 1992 murder of Denise Johnson in Arizona, a homicide detective found two seed pods from a paloverde tree in the bed of a pickup truck owned by the suspect, Mark Bogan. The accused man admitted having known the victim but denied ever having been near the site where her body was found. It so happened that there was a paloverde tree at the site, and testing showed that the DNA in the pods on his truck bed matched that of the tree itself. Bogan became the first suspect ever convicted by a plant.

On the other hand, in some cases, DNA evidence has cleared a suspect falsely accused. Such was the case with Kerry Kotler, convicted in 1981 for rape, robbery, and burglary and sentenced to 25–50 years in jail. In 1988, Kotler began petitioning for DNA analysis, which subsequently showed that his DNA did not match that of the rapist, who had left a semen sample in the victim's underwear. Kotler was released in December 1992 and in March 1996 was awarded $1.5 million in damages for his wrongful imprisonment. The story does not end there, however.

Kotler's case turned out to be one of the more bizarre in the annals of forensic DNA testing. Perhaps he did not commit the first rape, but a month after he received the damage award, he was on his way back to prison for the August 1995 rape of another victim. This time prosecutors showed that Kotler's semen matched samples taken from his victim's clothing—and to prove their case, they used DNA testing.

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HEREDITY

CONCEPT

Heredity is the transmission of genetic characteristics from ancestor to descendant through the genes. As a subject, it is tied closely to genetics, the area of biological study concerned with hereditary traits. The study of heritable traits helps scientists discern which are dominant and therefore are likely to be passed on from one parent to the next generation. On the other hand, a recessive trait will be passed on only if both parents possess it. Among the possible heritable traits are genetic disorders, but study in this area is ongoing, and may yield many surprises.

HOW IT WORKS

Heredity and Genetics

As discussed at the beginning of the essay on genetics, the subjects of genetics and heredity are inseparable from each other, but there are so many details that it is extremely difficult to wrap one's mind around the entire concept. It is advisable, then, to break up the overall topic into more digestible bits. One way to do this is to study the biochemical foundations of genetics as a subject in itself, as is done in Genetics, and then to investigate the impact of genetic characteristics on inheritance in a separate context, as we do here.

Also included in the present essay is a brief history of genetic study, which reveals something about the way in which these many highly complex ideas fit together. Many brilliant minds have contributed to the modern understanding of genetics and heredity; unfortunately, within the present context, space permits the opportunity to discuss only a few key figures. The first—a man whose importance in the study of genetics is comparable to that of Charles Darwin (1809–1882) in the realm of evolutionary studies—was the Austrian monk and botanist Gregor Mendel (1822–1884).

GENES. For thousands of years, people have had a general understanding of genetic inheritance—that certain traits can be, and sometimes are, passed along from one generation to the next—but this knowledge was primarily anecdotal and derived from casual observation rather than from scientific study. The first major scientific breakthrough in this area came in 1866, when Mendel published the results of a study on the hybridization of plants in which he crossed pea plants of the same species that differed in only one trait.

Mendel bred these plants over the course of several successive generations and observed the characteristics of each individual. He found that certain traits appeared in regular patterns, and from these observations he deduced that the plants inherited specific biological units from each parent. These units, which he called *factors,* today are known as *genes,* or units of information about a particular heritable trait. From his findings, Mendel formed a distinction between genotype and phenotype that is still applied by scientists studying genetics. Genotype may be defined as the sum of all genetic input to a particular individual or group, while phenotype is the actual observable properties of that organism. We return to the subjects of genotype and phenotype later in this essay.

MUTATION AND DNA. Although Mendel's theories were revolutionary, the scientific establishment of his time treated these new

ideas with disinterest, and Mendel died in obscurity. Then, in 1900, the Dutch botanist Hugo De Vries (1848–1935) discovered Mendel's writings, became convinced that his predecessor had made an important discovery, and proceeded to take Mendel's theories much further. Unlike the Austrian monk, De Vries believed that genetic changes occur in big jumps rather than arising from gradual or transitional steps. In 1901 he gave a name to these big jumps: mutations. Today a mutation is defined as an alteration of a gene, which contains something neither De Vries nor Mendel understood: deoxyribonucleic acid, or DNA.

Actually, DNA, a molecule that contains genetic codes for inheritance, had been discovered just four years after Mendel presented his theory of factors. In 1869 the Swiss biochemist Johann Friedrich Miescher (1844–1895) isolated a substance from the remnants of cells in pus. The substance, which contained both nitrogen and phosphorus, separated into a protein and an acid molecule and came to be known as nucleic acid. A year later he discovered DNA itself in the nucleic acid, but more than 70 years would pass before a scientist discerned its purpose.

THE DISCOVERY OF CHROMOSOMES. In the meantime, another major step in the history of genetics was taken just two years after De Vries outlined his mutation theory. In 1903 the American surgeon and geneticist Walter S. Sutton (1877–1916) discovered chromosomes, threadlike structures that split and then pair off as a cell divides in sexual reproduction. Today we know that chromosomes contain DNA and hold most of the genes in an organism, but that knowledge still lay in the future at the time of Sutton's discovery.

In 1910 the American geneticist Thomas Hunt Morgan (1866–1945) confirmed the relationship between chromosomes and heredity through experiments with fruit flies. He also discovered a unique pair of chromosomes called the sex chromosomes, which determine the sex of offspring. From his observation that a sex-specific chromosome was always present in flies that had white eyes, Morgan deduced that specific genes reside on chromosomes. A later discovery showed that chromosomes could mutate, or change structurally, resulting in a change of characteristics that could be passed on to the next generation.

DNA MAKES ITS APPEARANCE. All this time, scientists knew about the existence of DNA without guessing its function. Then, in the 1940s, a research team consisting of the Canadian-born American bacteriologist Oswald Avery (1877–1955), the American bacteriologist Maclyn McCarty (1911–), and the Canadian-born American microbiologist Colin Munro MacLeod (1909–1972) discovered the blueprint function of DNA. By taking DNA from one type of bacteria and inserting it into another, they found that the second form of bacteria took on certain traits of the first.

The final proof that DNA was the specific molecule that carries genetic information came in 1952, when the American microbiologists Alfred Hershey (1908–1997) and Martha Chase (1927–) showed that transferring DNA from a virus to an animal organ resulted in an infection, just as if an entire virus had been inserted. But perhaps the most famous DNA discovery occurred a year later, when the American biochemist James D. Watson (1928–) and the English biochemist Francis Crick (1916–) solved the mystery of the exact structure of DNA. Their goal was to develop a DNA model that would explain the blueprint, or language, by which the molecule provides necessary instructions at critical moments in the course of cell division and growth. To this end, Watson and Crick focused on the relationships between the known chemical groups that compose DNA. This led them to propose a double helix, or spiral staircase, model, which linked the chemical bases in definite pairs. Using this twisted-ladder model, they were able to explain how the DNA molecule could duplicate itself, since each side of the ladder contains a compound that fits with a compound on the opposite side. If separated, each would serve as the template for the formation of its mirror image.

Autosomes and Sex Chromosomes

Genetic information is organized into chromosomes in the nucleus, or control center, of the cell. Human cells have 46 chromosomes each, except for germ, or reproductive, cells (i.e., sperm cells in males and egg cells in females), which each have 23 chromosomes. Each person receives 23 chromosomes from the mother's egg and 23 chromosomes from the father's sperm. Of these 23 chromosomes, 22 are called autosomes, or



IF TWO GROUPS OF THE SAME SPECIES ARE SEPARATED FOR A LONG TIME, GENETIC DRIFT MAY LEAD TO THE FORMATION OF DISTINCT SPECIES, AS WHEN THE COLORADO RIVER CUT OPEN THE GRAND CANYON AND ISOLATED THE KAIBAB SQUIRREL OF THE NORTH RIM FROM THE ABERT SQUIRREL (SHOWN HERE) OF THE SOUTH. *(© W. Perry Conway/Corbis. Reproduced by permission.)*

non-sex chromosomes, meaning that they do not determine gender. The remaining chromosome, the sex chromosome, is either an X or a Y. Females have two Xs (XX), and males have one of each (XY), meaning that females can pass only an X to their offspring, whereas males can pass either an X or a Y. (This, in turn, means that the sperm of the father determines the gender of the offspring.)

ALLELES

The 44 autosomes have parallel coded information on each of the two sets of 22 autosomes, and this coding is organized into genes, which provide instructions for the synthesis (manufacture) of specific proteins. Each gene has a set locus, or position, on a particular chromosome, and for each locus, there are two slightly different forms of a gene. These differing forms, known as alleles, each represent slightly different codes for the same trait. One allele, for instance, might say "attached earlobe," meaning that the bottom of the lobe is fully attached to the side of the head and cannot be flapped. Another allele, however, might say "unattached earlobe," indicating a lobe that is not fully attached and therefore can be flapped.

DOMINANT AND RECESSIVE ALLELES. Each person has two alleles of the same gene—the genotype for a single locus. These can be written as uppercase or lowercase letters of the alphabet, with capital letters defining dominant traits and lowercase letters indicating recessive traits. A dominant trait is one that can manifest in the offspring when inherited from only one parent, whereas a recessive trait must be inherited from both parents in order to manifest. For instance, brown eyes are dominant and thus would be represented in shorthand with a capital B, whereas blue eyes, which are recessive, would be represented with a lowercase b. Genotypes are either homozygous (having two identical alleles, such as BB or bb) or heterozygous (having different alleles, such as Bb). The phenotype, however—that is, the actual eye color—must be one or the other, because both sets of genes cannot be expressed together.

Unless there is some highly unusual mutation, a child will not have one brown eye and one blue eye; instead, the dominant trait will overpower the recessive one and determine the eye color of the child. If an individual's genotype is BB or Bb, that person definitely will have brown eyes; the only way for the individual to have blue eyes is if the genotype is bb—meaning that both parents have blue eyes. Oddly, two parents with brown eyes could produce a child with blue eyes. How is that possible? Suppose both the mother and the father had the heterozygous alleles Bb—a dominant brown and a recessive blue. There is then a 25% chance that the child could inherit both parents' recessive genes, for a bb genotype—and a blue-eyed phenotype.

LEARNING FROM HEREDITARY LAW. What we have just described is called *genetic dominance,* or the ability of a single allele to control phenotype. This principle of classical Mendelian genetics does not explain everything. For example, where height is concerned, there is not necessarily a dominant or recessive trait; rather, offspring typically have a height between that of the parents, because height also is determined by such factors as diet. (Also, more than one pair of genes is involved.) Hereditary law does, however, help us predict everything from hair and eye color to genetic dis-

orders. As with the blue-eyed child of brown-eyed parents, it is possible that neither parent will show signs of a genetic disorder and yet pass on a double-recessive combination to their children. Again, however, other factors—including genetic ones—may come into play. For example, Down syndrome (discussed in Mutation) is caused by abnormalities in the number of chromosomes, with the offspring possessing 47 chromosomes instead of the normal 46.

REAL-LIFE APPLICATIONS

Population Genetics

Studies in heredity and genetics can be applied not only to an individual or family but also to a whole population. By studying the gene pool (the sum of all the genes shared by a population) for a given group, scientists working in the field of population genetics seek to explain and understand specific characteristics of that group. Among the phenomena of interest to population geneticists is genetic drift, a natural mechanism for genetic change in which specific traits coded in alleles change by chance over time, especially in small populations, as when organisms are isolated on an island. If two groups of the same species are separated for a long time, genetic drift may lead even to the formation of distinct species from what once was a single life-form. When the Colorado River cut open the Grand Canyon, it separated groups of squirrels that lived in the high-altitude pine forest. Over time, populations ceased to interbreed, and today the Kaibab squirrel of the north rim and the Abert squirrel of the south are different species, no more capable of interbreeding than humans and apes.

Where humans are concerned, population genetics can aid, for instance, in the study of genetic disorders. As discussed in Mutation, certain groups are susceptible to particular conditions: thus, cystic fibrosis is most common among people of northern European descent, sickle cell anemia among those of African and Mediterranean ancestry, and Tay-Sachs disease among Ashkenazim, or Jews whose ancestors lived in eastern Europe. Studies in population genetics also can supply information about prehistoric events. As a result of studying the DNA in fossil records, for example, some scientists have reached the conclusion that the migration of peoples from Siberia to North America in about 11,000 B.C. took place in two distinct waves.



THERE ARE SEVERAL THOUSAND GENETIC DISORDERS, CLASSIFIED INTO AUTOSOMAL DOMINANT, AUTOSOMAL RECESSIVE, SEX-LINKED, AND MULTIFACTORIAL TYPES. DWARFISM, FOR EXAMPLE, CAN BE CAUSED BY ACHONDROPLASIA, TRANSMITTED BY A GENE INHERITED FROM ONE PARENT (DOMINANT), OR BY A GROWTH HORMONE DEFICIENCY, TRANSMITTED BY GENES INHERITED FROM BOTH PARENTS (RECESSIVE). *(© Photo Researchers. Reproduced by permission.)*

Genetic Disorders

There are several thousand genetic disorders, which can be classified into one of several groups: autosomal dominant disorders, which are transmitted by genes inherited from only one parent; autosomal recessive disorders, which are transmitted by genes inherited from both parents; sex-linked disorders, or ones associated with the X (female) and Y (male) chromosome; and multifactorial genetic disorders. If one parent has an autosomal dominant disorder, the offspring have a 50% chance of inheriting that disease. Approximately 2,000 autosomal dominant disorders have been identified, among them Huntington disease, achondroplasia (a type of

KEY TERMS

ALLELE: For any locus, one of two (or more) slightly different forms of a gene. These differing forms mean that alleles code for different versions of the same trait.

AUTOSOMES: The 22 non-sex chromosomes.

CHROMOSOME: A DNA-containing body, located in the cells of most living things, that holds most of the organism's genes.

DNA: Deoxyribonucleic acid, a molecule in all cells, and many viruses, that contains genetic codes for inheritance.

DOMINANT: In genetics, a term for a trait that can manifest in the offspring when inherited from only one parent. Its opposite is *recessive.*

GENE: A unit of information about a particular heritable trait. Usually stored on chromosomes, genes contain specifications for the structure of a particular polypeptide or protein.

GENE POOL: The sum of all the genes shared by a population, such as that of a species.

GENETIC DISORDER: A condition, such as a hereditary disease, that can be traced to an individual's genetic makeup.

GENETIC DOMINANCE: The ability of a single allele to control phenotype.

GENOTYPE: The sum of all genetic input to a particular individual or group.

GERM CELL: One of two basic types of cells in a multicellular organism. In contrast to somatic, or body, cells, germ cells are involved in reproduction.

HEREDITY: The transmission of genetic characteristics from ancestor to descendant through the genes.

HETEROZYGOUS: Having two different alleles—for example, Bb.

HOMOZYGOUS: Having two identical alleles, such as BB or bb.

LOCUS: The position of a particular gene on a specific chromosome.

MUTATION: Alteration in the physical structure of an organism's DNA, resulting in a genetic change that can be inherited.

NUCLEUS: The control center of a cell, where DNA is stored.

PHENOTYPE: The actual observable properties of an organism, as opposed to its genotype.

RECESSIVE: In genetics, a term for a trait that can manifest in the offspring only if it is inherited from both parents. Its opposite is *dominant.*

SEX CHROMOSOMES: Chromosomes that determine gender. Human females have two X chromosomes (XX), and males have an X and a Y (XY).

SYNTHESIZE: To manufacture chemically, as in the body.

dwarfism), Marfan syndrome (extra-long limbs), polydactyly (extra toes or fingers), some forms of glaucoma (a vision disorder), and hypercholesterolemia (high levels of cholesterol in the blood).

The first two are discussed in Mutation. Marfan syndrome, or arachnodactyly ("spider arms"), is historically significant because it is believed that Abraham Lincoln suffered from that condition. Some scientists even maintain

that his case of Marfan, a disease sometimes accompanied by eye and heart problems, was so severe that he probably would have died six months or a year after the time of his actual death by assassination at age 56 in April 1865.

RECESSIVE GENE DISORDERS. Just as a person has a 25% chance of inheriting two recessive alleles, so two parents who each have a recessive gene for a genetic disorder stand a 25% chance of conceiving a child with that disorder. Among the approximately 1,000 known recessive genetic disorders are cystic fibrosis, sickle cell anemia, Tay-Sachs disease, galactosemia, phenylketonuria, adenosine deaminase deficiency, growth hormone deficiency, Werner syndrome (juvenile muscular dystrophy), albinism (lack of skin pigment), and autism. Several of these conditions are discussed briefly elsewhere, and albinism is treated at length in Mutation. Note that all of the disorders mentioned earlier, in the context of population genetics, are recessive gene disorders. Phenylketonuria (see Metabolism) and galactosemia are examples of metabolic recessive gene disorders, in which a person's body is unable to carry out essential chemical reactions. For example, people with galactosemia lack an enzyme needed to metabolize galactose, a simple sugar that is found in lactose, or milk sugar. If they are given milk and other foods containing galactose early in life, they eventually will suffer mental retardation.

SEX-LINKED GENETIC DISORDERS. Dominant sex-linked genetic disorders affect females, are usually fatal, and—fortunately—are rather rare. An example is Albright hereditary osteodystrophy, which brings with it seizures, mental retardation, and stunted growth. On the other hand, several recessive sex-linked genetic disorders are well known, though at least one of them, color blindness, is relatively harmless. Among the more dangerous varieties of these disorders, which are passed on to sons through their mothers, the best known is hemophilia, discussed in Noninfectious Diseases. Many recessive sex-linked genetic disorders affect the immune, muscular, and nervous systems and are typically fatal. An example is severe combined immune deficiency syndrome (SCID), which is characterized by a very poor ability to combat infection. The only known cure for SCID is bone marrow transplantation from a close relative. Short of a cure, patients may be forced to live enclosed in a large plastic bubble that protects them from germs in the air. From this sad fact derives the title of an early John Travolta movie, *The Boy in the Plastic Bubble* (1976), based on the true story of the SCID victim Tod Lubitch. (The ending, in which Travolta, as Tod, leaves his bubble and literally rides off into the sunset with his beautiful neighbor Gina, is more Hollywood fiction than fact. Lubitch actually died in his early teens, shortly after receiving a bone marrow transplant.)

MULTIFACTORIAL GENETIC DISORDERS. Scientists often find it difficult to determine the relative roles of heredity and environment in certain medical disorders, and one way to answer this question is with statistical and twin studies. Identical and fraternal twins who have been raised in different and identical homes are evaluated for multifactorial genetic disorders. Multifactorial genetic disorders include medical conditions associated with diet and metabolism, among them obesity, diabetes, alcoholism, rickets, and high blood pressure. Other such multifactorial conditions are a tendency toward certain infectious diseases, such as measles, scarlet fever, and tuberculosis; schizophrenia and some other psychological illnesses; clubfoot and cleft lip; and various forms of cancer. The tendency of a particular person to be susceptible to any one of these disorders is a function of that person's genetic makeup, as well as environmental factors.

Breeding within the Family

If there is one thing that most people know about heredity and breeding, it is that a person should never marry or conceive offspring with close relatives. Aside from moral restrictions, there is the fear of the genetic defects that would result from close interbreeding. How close is too close? Certainly, first cousins are off-limits as potential mates, though second or third cousins (people who share the same great-grandparents and the same great-great-grandparents, respectively) are probably far enough apart. Hence, the phrase "kissin' cousins," meaning a relative who is a distant enough to be considered a potential partner.

What kind of defects? Hemophilia, mentioned earlier, is popularly associated with royalty because several members of European ruling houses around the turn of the nineteenth century had it. Common wisdom maintains that the tendency toward the disease resulted from the

fact that royalty were apt to marry close relatives. In fact, hemophilia has nothing to do with royalty per se and certainly bears no relation to marriages between close relatives. Research findings gathered over the course of more than three decades, beginning in 1965, indicate that many views about first cousins marrying may be more a matter of tradition than of scientific fact. According to information published in the *Journal of Genetic Counseling* and reported in the *New York Times* in April 2002, first cousins who have children together face only a slightly higher risk than parents who are completely unrelated. For example, within the population as a whole, the risk that a child will be born with a serious defect, such as cystic fibrosis, is 3-4%, while first cousins who conceive a child typically add another 1.7-2.8 percentage points of risk. Although this represents nearly double the risk, it is still a very small factor.

Researchers were quick to point out that mating should not take place between persons more closely related than first cousins. According to Denise Grady in the *New York Times,* "The report made a point of saying that the term 'incest' should not be applied to cousins, but only to sexual relations between siblings or between parents and children." First cousins, on the other hand, are a quite different matter, a fact borne out by the long history of people who married their first cousins. One example was Charles Darwin, who fathered many healthy children with his cousin, Emma Wedgwood.

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GENETIC ENGINEERING

CONCEPT

Genetic engineering is the alteration of genetic material by direct intervention in genetic processes with the purpose of producing new substances or improving functions of existing organisms. It is a very young, exciting, and controversial branch of the biological sciences. On the one hand, it offers the possibility of cures for diseases and countless material improvements to daily life. Hopes for the benefits of genetic engineering are symbolized by the Human Genome Project, a vast international effort to categorize all the genes in the human species. On the other hand, genetic engineering frightens many with its potential for misuse, either in Nazi-style schemes for population control or through simple bungling that might produce a biological holocaust caused by a man-made virus. Symbolic of the alarming possibilities is the furor inspired by a single concept on the cutting edge of genetic engineering: cloning.

HOW IT WORKS

DNA

Any discussion of genetics makes reference to DNA (deoxyribonucleic acid), a molecule that contains genetic codes for inheritance. DNA resides in chromosomes, threadlike structures found in the nucleus, or control center, of every cell in every living thing. Chromosomes themselves are made up of genes, which carry codes for the production of proteins. The latter, of which there are many thousands of different varieties, make up the majority of the human body's dry weight.

Although it is central to the latest advances in modern genetic research, DNA was discovered more than 130 years ago. In 1869 the Swiss biochemist Johann Friedrich Miescher (1844–1895) isolated a substance, containing both nitrogen and phosphorus, that separated into a protein and an acid molecule. He called it *nucleic acid,* and in this material he discovered DNA. Some 74 years would pass, however, before scientists recognized the function of the nucleic acid Miescher had discovered. Then, in 1944, a research team led by the Canadian-born American bacteriologist Oswald Avery (1877–1955) found that by taking DNA from one type of bacterium and inserting it into another, the second bacterium took on certain traits of the first. This experiment, along with other experiments and research, proved that DNA serves as a blueprint for the characteristics and functions of organisms.

THE DOUBLE HELIX. Nine years later, in 1953, the American biochemist James D. Watson (1928–) and the English biochemist Francis Crick (1916–) solved the mystery of DNA's structure and explained the means by which it provides necessary instructions at critical moments in the course of cell division and growth. They proposed a double helix, or spiral staircase, model, which linked the chemical bases of DNA in definite pairs. Using this twisted-ladder model, they were able to explain how the DNA molecule could duplicate itself, since each side of the ladder is identical to the other; if separated, each would serve as the template for the formation of its mirror image.

The sides of the DNA ladder are composed of alternating sugar and phosphate molecules, like links in a chain, and consist of four different chemical bases: adenine, guanine, cytosine, and



Computer model of DNA, showing its double helix, or spiral staircase, form, which links the chemical bases of DNA in pairs. Each side of the ladder is identical to the other; if separated, each would serve as the template for the formation of its mirror image. *(© Kenneth Eward/Grafz/Science Source/Photo Researchers. Reproduced by permission.)*

thymine. The four letters designating these bases—A, G, C, and T—are the alphabet of the genetic code, and each rung of the DNA molecule is made up of a combination of two of these letters. Owing to specific chemical affinities, A always combines with T and C with G, to form what is called a base pair. Specific sequences of these base pairs, which are bonded to each other by atoms of hydrogen, constitute the genes.

ENDLESS COMBINATIONS. A four-letter alphabet may seem rather small for constructing the extensive vocabulary that defines the myriad life-forms on Earth. If one stops to consider the exponential operations involved, however, it is easy to understand how large the range of possibilities can become. For any sequence, there are four possibilities for the first two letters (AT, TA, CG, or GC) and four more possibilities for the second two letters. Thus, just for a four-letter sequence, there are 16 possibilities, and for each pair of letters added to the sequence, the total is multiplied by four.

To see where this might lead, imagine that you started with a penny and tried to quadruple your funds every day. The first day there would not be a dramatic increase, since you would have to earn only $0.04, and even by day 4 you would need only $2.56 to meet your goal. But as the quadrupling process continued, day by day the sums of money would get bigger ($655.36 on day 8) and bigger ($16,772.16 on day 12) and bigger ($687,194,767.36 on day 18). Given the fact that the human body contains an almost unfathomable number of genes, each of which may be between 2,000 and 200,000 base pairs long, one can begin to imagine just how large the number of possibilities would become.

Each one of these combinations has a different meaning, providing the code for all manner of specific traits, such as brown hair and blue eyes, dimples, unattached earlobes, and so on. Except for identical twins, no two humans have exactly the same genetic information. What follows are just a few facts about the human genome—that is, all of the genetic material in the chromosomes of the human organism:

Some Facts About the Human Genome

- The human body contains about 100 trillion cells.
- Each cell has a DNA code consisting of some 1.5 billion base pairs.
- The DNA in each cell, if stretched to its full length, would be 6 ft. (1.8 m) long—yet it fits into a space about 0.0004 in. (0.0001 cm) across, smaller than the head of a pin.
- If all of the DNA in the human body were stretched end to end, it would reach to the Sun and back more than 600 times.
- If a person attempted to recite the entire human genome, with all its base pairs, at the rate of one letter per second, 24 hours a day, it would take a century.
- Every second scientists working on the Human Genome Project are decoding some 12,000 letters of DNA.
- Our DNA is 98% identical to that of chimpanzees.
- Only 0.2% of all human DNA differs between individuals; in other words, people are 99.8% the same, and all the vast differences between people are a product of just 1/500th of the total DNA.
- Despite all that scientists know about DNA, a staggering 97% of all human DNA has no known function.

PRINCIPLES OF GENETIC ENGINEERING

Just as DNA is at the core of studies in genetics, recombinant DNA (rDNA)—that is, DNA that has been genetically altered through a process known as *gene splicing*—is the focal point of genetic engineering. In gene splicing, a DNA strand is cut in half lengthwise and joined with a strand from another organism or perhaps even another species. Use of gene splicing makes possible two other highly significant techniques. Gene transfer, or incorporation of new DNA into an organism's cells, usually is carried out with the help of a microorganism that serves as a vector, or carrier. Gene therapy is the introduction of normal or genetically altered genes to cells, generally to replace defective genes involved in genetic disorders.

DNA also can be cut into shorter fragments through the use of restriction enzymes. (An enzyme is a type of protein that speeds up chemical reactions.) The ends of these fragments have an affinity for complementary ends on other DNA fragments and will seek those out in the target DNA. By looking at the size of the fragment created by a restriction enzyme, investigators can determine whether the gene has the proper genetic code. This technique has been used to analyze genetic structures in fetal cells and to diagnose certain blood disorders, such as sickle cell anemia.

GENE TRANSFER. Suppose that a particular base-pair sequence carries the instruction "make insulin"; if a way could be found to insert that base sequence into the DNA of bacteria, for example, those bacteria would be capable of manufacturing insulin. This, in turn, would greatly improve the lives of people with type 1 diabetes, who depend on insulin shots to aid their bodies in processing blood sugar. (See Noninfectious Diseases for more about diabetes.)

Although the concept of gene transfer is relatively simple, its execution presents considerable technical obstacles. The first person to surmount these obstacles was the American biochemist Paul Berg (1926–), often referred to as the "father of genetic engineering." In 1973 Berg developed a method for joining the DNA from two different organisms, a monkey virus known as *SV40* and a virus called *lambda phage.* Although the accomplishment was clearly a breakthrough, Berg's method was difficult. Then, later that year, the American biochemists Stanley Cohen (1922–) at Stanford University, and Herbert Boyer (1936–) at the University of California at San Francisco discovered an enzyme that greatly increased the efficiency of the Berg procedure. The gene-transfer technique developed by Berg, Boyer, and Cohen formed the basis for much of the ensuing progress in genetic engineering.

REAL-LIFE APPLICATIONS

BIG BUSINESS IN DNA

Ever since the breakthrough discoveries of Watson, Crick, and others in the 1950s made genetic engineering a possibility, the new field has promised increasingly bigger payoffs. These payoffs take the form of improvements to human life and profits to those who facilitate those improvements. The possible applications of genetic engineering are virtually limitless—as are the profits to be made from genetic engineering as a business. As early as the 1970s, entrepreneurs (independent businesspeople) recognized the commercial potential of genetically engineered products, which promised to revolutionize life, technology, and commerce as computers also were doing. Thus was born one of the great buzzwords of the late twentieth century: biotechnology, or the use of genetic engineering for commercial purposes.

Several early biotechnology firms were founded by scientists involved in fundamental research: Boyer, for example, teamed up with the venture capitalist Robert Swanson in 1976 to form Genentech (Genetic Engineering Technology). Other pioneering companies, including Cetus, Biogen, and Genex, likewise were founded through the collaboration of scientists and businesspeople. Today biotechnology promises a revolution in numerous areas, such as agriculture. Recombinant DNA techniques enable scientists to produce plants that are resistant to freezing temperatures, that will take longer to ripen, that will develop their own resistance to pests, and so on. By 1988 scientists had tested more than two dozen kinds of plants engineered to have special properties such as these. Yet no field of biotechnology and genetic engineering is as significant as the applications to health and the cures for diseases.

MEDICINES AND CURES. The use of rDNA allows scientists to produce many products that were previously available only in limited quantities: for example, insulin, which we referred to earlier. Until the 1980s the only source of insulin for people with diabetes came from animals slaughtered for meat and other purposes. The supply was never high enough to meet demand, and this drove up prices. Then, in 1982, the U.S. Food and Drug Administration (FDA) approved the sale of insulin produced by genetically altered organisms—the first such product to become available. Since 1982 several additional products, such as human growth hormone, have been made with rDNA techniques.

One of the most exciting potential applications of genetic engineering is the treatment of genetic disorders, which are discussed in Heredity, through the use of gene therapy. Among the more than 3,000 such disorders, quite a few of which are quite serious or even fatal, many are the result of relatively minor errors in DNA sequencing. Genetic engineering offers the potential to provide individuals with correct copies of a gene, which could make possible a cure for that condition. In the 1980s scientists began clinical trials of a procedure known as *human gene therapy* to replace defective genes. The technique, still very much in the developmental stage, offers the hope of cures for diseases that medicine has long been powerless to combat.

In 2001 scientists at the Weizmann Institute in Israel brought together two of the most exciting fields of research, biotechnology and computers, to produce the DNA-processing nanocomputer. It is an actual computer, but it is so small that a trillion of them would fit in a test tube. It consists of DNA and DNA-processing enzymes, both dissolved in liquid; thus its input, output, and software are all in the form of DNA molecules. The purpose of the nanocomputer is to analyze DNA, detecting abnormalities in the human body and creating remedies for them.

The Human Genome Project

At the center of genetic studies, with vast potential applications to genetic engineering, is the Human Genome Project (HGP), an international effort to analyze and map the DNA of humans and several other organisms. As discussed in the essay Genetics, the HGP began with efforts by the Atomic Energy Commission, a predecessor to the U.S. Department of Energy, to study the genetic effects of radioactive nuclear fallout. In 1990 the Department of Energy in cooperation with the National Institutes of Health (NIH), launched the project. At about the same time, the governments of the United Kingdom, Japan, Russia, France, and Italy initiated their own, similar undertakings, which are coordinated with American efforts.

The purpose of the project is to locate each human gene and determine its specific structure and function. Such knowledge will provide the framework for studies in health, disease, biology, and medicine during the twenty-first century and no doubt will make possible the cures for countless diseases. Although great strides have been made in gene therapy in a relatively short time, its potential usefulness has been limited by lack of scientific data concerning the multitude of functions that genes control in the human body. For gene therapy to advance to its full potential, scientists must discover the biological role of each of these genes and locate each base pair of which they are comprised.

A PROGRESS REPORT. Scientists participating in the project have identified an average of one new gene a day, and this rate of discovery has increased. At the time of its establishment in 1990 (under the leadership of James D. Watson, who served as director until 1992), HGP was expected to reach completion by 2005. In 2002, however, the project's leadership predicted completion by some time in the following year. Along the way, they had discovered that the human genome, originally believed to include 100,000 to as many as 150,000 genes, actually consists of about 30,000 to 40,000 genes.

Both HGP and a private firm, Celera Genomics (founded 1998), had undertaken the study of the human genome, and in June 2000 the entities jointly reported that they had finished the initial sequencing of the three billion-odd base pairs in the human genome. By that point, researchers also had completed thorough DNA sequences for many other organisms. The basis for the latter undertaking is that humans share many genes with other life-forms. With the completion of initial sequencing, scientists working on the HGP undertook the effort of determining the exact sequence of the base pairs that make them up all human genes. Long before completion, the project had yielded some infor-

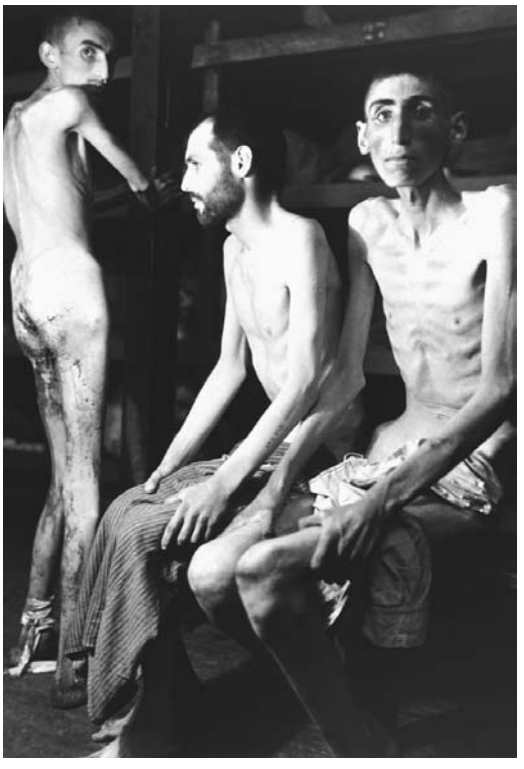
mation. Some of the genes identified through the HGP include one that guides reproduction of the human immunodeficiency virus (HIV), which causes the acquired immunodeficiency syndrome, better known as AIDS (see Infectious Diseases). Researchers also have located a gene that predisposes people to obesity as well as genes associated with such inherited disorders as Huntington disease, Lou Gehrig disease (also called amyotrophic lateral sclerosis, or ALS), and some colon and breast cancers.

A World of Controversy

The HGP has numerous implications—and not all of them, in the minds of some critics, are positive. The NIH inadvertently created cause for concern when, in 1991, it attempted to patent certain forms of DNA. While patenting is touted as a necessary financial incentive for research initiatives, critics maintain that it restricts access to the information generated and to the use of those discoveries. That places a great deal of control in the hands of the private firm that funded the research and may limit the spread of real benefits that result from discovery.

Some scientists and politicians have raised the concern that the ability to produce detailed genetic information on people could give too much power to the people who possess that knowledge. Most states do not have laws protecting citizens against the misuse of genetic information, for instance, by employers and insurers. In the absence of effective legal remedies, genetic testing may be used to bar people from employment or insurance coverage. Insurers may even make mandatory testing a requirement for coverage. Existing laws may not be adequate to protect people's privacy: whereas the individual may be protected from having to provide potentially damaging genetic information, such information still can be obtained by testing the individual's relatives.

NIGHTMARISH IMAGES. The idea of genetic information being used to control a person's destiny calls to mind all sorts of nightmarish images, such as those raised by the movie *Gattaca* (1997). Set in a dystopian, or anti-utopian, future, the film depicts a character who employs elaborate means to conceal his true identity in order to hold on to a job that otherwise would be forbidden to him because of his DNA. In fact, one does not have to go to fiction to find examples of societies and movements that have used genetics as a form of social control.



STARVING PRISONERS OF A NAZI CONCENTRATION CAMP, ONE FRIGHTENING EXAMPLE OF THE ATTEMPT TO USE GENETICS AS A FORM OF SOCIAL CONTROL. NAZI GERMANY PRACTICED MASS MURDER OF JEWS AND OTHERS WHO WERE DEEMED TO HAVE "UNDESIRABLE" TRAITS. *(© Corbis. Reproduced by permission.)*

The most frightening example of this was Nazi Germany, which practiced mass murder not only of Jews and other ethnic and social groups but also of people who suffered from mental retardation or other "undesirable" traits. The purpose of DNA was discovered only a year before the collapse of the Nazi empire in 1945, and one can only imagine what Adolf Hitler and his minions would have done with this knowledge if they had had access to it. (DNA is one of several scientific and technological concepts that came to fruition at the end of World War II but which Hitler, fortunately, was unable to use to his advantage. Others include rocketry, nuclear weaponry, radar, computers, and television.)

Nazism was actually an especially repugnant version of a movement known as *eugenics,* which had its origins in the late nineteenth and early twentieth centuries. Based on the idea that populations could be improved by encouraging people with "positive" traits to reproduce while discour-



On February 24, 1997, the first mammal cloned from an adult cell, a lamb named Dolly (shown here as an adult), was born in Edinburgh, Scotland. *(Photograph by Jeff Mitchell. Archive Photos. Reproduced by permission.)*

aging reproduction among those with less desirable traits, eugenics was at one time a mainstream movement whose adherents included the distinguished U.S. Supreme Court justice Oliver Wendell Holmes, Jr. (1841–1935).

OTHER CONCERNS. The specter of eugenics raises the threat that a single human, or a group of humans, could "play God" with the lives of others. Another dramatic fear associated with genetic engineering is the threat that a genetically re-engineered virus could turn out to be extremely virulent, or deadly, and spread. There are other, more mundane questions of ethics: for instance, is it appropriate for scientists to establish private, for-profit corporations to benefit from discoveries they made while working for public-sponsored research institutions? No wonder, then, that the budget for the HGP in the United States includes a small allocation (3% of its total) toward study of the ethical, legal, and social implications (ELSI) of the project. The ELSI Working Group is charged with studying the issues of fairness, privacy, delivery of health care, and education. Meanwhile, there is a vast body of opposition to genetic engineering, biotechnology, and the HGP. And no aspect of the larger subject is more upsetting to certain individuals, as well as special interest groups, as that of cloning.

Cloning

A clone is a cell, group of cells, or organism that contains genetic information identical to that of the parent cell or organism. It is a form of asexual reproduction (see Reproduction), and as such it is not as new as it seems; what *is* new, however, is humans' ability to manipulate cloning at the genetic level. The first clones produced by humans as long as 2,000 years ago were plants developed from grafts and stem cuttings. By cloning—a process that calls into play complex laboratory techniques and the use of DNA replication—people usually mean a relatively recent scientific advance. Among these techniques is the ability to isolate and copy (that is, to clone) individual genes that direct an organism's development.

THE PROMISE OF CLONING. The cloning of specific genes can provide large numbers of copies of that gene for use in genetic and taxonomic research as well as in the practical areas of medicine and farming. In the latter field, the goal is to clone plants with specific traits that make them superior to naturally occurring organisms. For example, in 1985 scientists conducted field tests using clones of plants whose genes had been altered in the laboratory to generate resistance to insects, viruses, and bacteria. New strains of plants resulting from cloning could produce crops that can grow in poor soil or even underwater and fruits and vegetables with improved nutritional qualities and longer shelf lives. A cloning technique known as *twinning* could induce livestock to give birth to twins or even triplets, and on the environmental front cloning might help save endangered species from extinction.

In the realm of medicine and health, cloning has been used to make vaccines and hormones. It has become possible, by combining two different kinds of cells (such as mouse and human cancer cells), to produce large quantities of specific antibodies, via the immune system, to fight off disease. When injected into the bloodstream, these cloned antibodies seek out and attack disease-causing cells anywhere in the body. By attaching

a tracer element to the cloned antibodies, scientists can locate hidden cancers, and by attaching specific cancer-fighting drugs, the treatment dose can be transported directly to the cancer cells.

EXPERIMENTS IN CLONING. The modern era of laboratory cloning began in 1958 when the British plant physiologist F. C. Steward (1904–1993) cloned carrot plants from mature single cells placed in a nutrient culture containing hormones. The first cloning of animal cells took place in 1964, when the British molecular biologist John B. Gurdon (1933–1989) took nuclei from intestinal cells of toad tadpoles and injected them into unfertilized eggs. The cell nuclei in the eggs had been destroyed with ultraviolet light, but when the eggs were incubated, Gurdon found that 1–2% of the eggs developed into fertile, adult toads.

The first successful cloning of mammals occurred nearly 20 years later, when scientists in Switzerland and the United States successfully cloned mice using a method similar to Gurdon's approach. Their method required one extra step, however: after taking the nuclei from the embryos of one type of mouse, they transferred them into the embryos of another type of mouse. The latter served as a surrogate, or replacement, mother. The cloning of cattle livestock was tried first in 1988, when embryos from prize cows were transplanted to unfertilized cow eggs whose own nuclei had been removed. An even greater breakthrough transpired on February 24, 1997, with the birth of a lamb named Dolly in Edinburgh, Scotland. Dolly was no ordinary sheep: she was the first mammal born from the cloning of an adult cell. Thus, she had been produced by asexual reproduction in the form of genetically engineered cloning rather than by anything resembling a normal process. Nonetheless, she proved her own ability to reproduce the old-fashioned way when, on April 23, 1998, she gave birth to a daughter named Bonnie.

ARE HUMANS NEXT? Though Dolly's and Bonnie's births excited hopes, they also inspired fears. If large mammals could be cloned, could humans? As early as 1993 an attempt had been made at cloning human embryos as part of studies on *in vitro* (out of the body) fertilization. The purpose was to develop fertilized eggs in test tubes and then to implant them into the wombs of women having difficulty becoming pregnant. These fertilized eggs, however, did not develop to a stage that was suitable for transplantation into a human uterus. Then, on October 13, 2001, scientists at Advanced Cell Technology in Worcester, Massachusetts, successfully cloned a human embryo. They had not created human life, as it might sound; what they had developed instead was a source for nerve and other tissues that could be harvested for use in medicine and research. Still, the news—overshadowed though it was in America, where people were still reeling from the September 11 terrorist attacks—was earth-shattering. Human cells had been reproduced, and once again it appeared that the production of human clones might be possible.

It is easy to understand how people might respond with alarm to such frightening news with alarm. Such fears have a great deal more to do with Hollywood than they do with science. In fact, the accomplishment of the Massachusetts firm, while impressive from a scientific standpoint, was fairly modest compared with the Frankenstein-like image presented by anti–genetic engineering scaremongers. "Cloned an embryo" actually sounds a great deal more dramatic than what the Massachusetts scientists achieved, with just one embryo reaching the size of six cells before the cells stopped dividing. This is hardly the beginnings of a clone army.

At any rate, the cloning practiced at the Massachusetts firm was therapeutic cloning, involving the production of genetic material for the treatment of specific conditions. It is a far cry from reproductive cloning, which entails implanting a cloned embryo in a uterus—and even that is still a long way from the clichéd image of clones produced in a test tube without any parents other than the biological material used to create them.

Such ideas are related much more closely to those highlighted in Aldous Huxley's 1932 novel *Brave New World* than they are to scientific realities. And even if humans wanted to develop such technology, it would be many, many years in the future. As for "creating life," to do so is probably not even possible; if it is, such an achievement is about as far off as travel to another solar system. This is not to say that all fears of cloning and genetic engineering are unwarranted; on the contrary, it is good to have a healthy level of skepticism. But it is also good to be an equal-opportunity skeptic and therefore to question ideas in the

KEY TERMS

AMINO ACIDS: Organic compounds made of carbon, hydrogen, oxygen, nitrogen, and (in some cases) sulfur bonded in characteristic formations. Strings of amino acids make up proteins.

BASE PAIR: A pair of chemicals that form the "rungs" on a DNA molecule, which has the shape of a spiral staircase.

BIOTECHNOLOGY: A name for the industry built around the application of genetic engineering techniques.

CHROMOSOME: A DNA-containing body, located in the cells of most living things, that holds most of the organism's genes.

CLONE: A cell, group of cells, or organism that contains genetic information identical to that of its parent cell or organism.

CLONING: A specialized genetic process whereby clones are produced. Cloning is a form of asexual reproduction.

DNA: Deoxyribonucleic acid, a molecule in all cells, and many viruses, that contains genetic codes for inheritance.

ENZYME: A protein material that speeds up chemical reactions in the bodies of plants and animals without itself taking part in or being consumed by those reactions.

GENE: A unit of information about a particular heritable trait. Usually stored on chromosomes, genes contain specifications for the structure of a particular polypeptide or protein.

GENE SPLICING: A process whereby recombinant DNA is formed by cutting a DNA strand in half lengthwise and joining it with a strand from another organism or perhaps even another species.

GENE THERAPY: The introduction of normal or genetically altered genes to cells, typically to replace defective genes involved in genetic disorders.

GENE TRANSFER: Incorporation of new DNA into an organism's cells, usually with the help of a microorganism that serves as a vector.

GENETIC DISORDER: A condition, such as a hereditary disease, that can be traced to an individual's genetic makeup.

GENETIC ENGINEERING: The alteration of genetic material by direct intervention in genetic processes with the purpose of producing new substances or improving functions of existing organisms.

NUCLEUS: The control center of a cell, where DNA is stored.

PROTEINS: Large molecules built from long chains of 50 or more amino acids. Proteins serve the functions of promoting normal growth, repairing damaged tissue, contributing to the body's immune system, and making enzymes.

RDNA: Recombinant DNA, or DNA that has been genetically altered through gene splicing.

RESTRICTION ENZYMES: Enzymes that break DNA into fragments at particular sites.

VECTOR: In the context of genetics, a vector is a microorganism or virus that is used to transfer DNA from one organism to another.

popular culture—including opposition to genetic engineering.

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MUTATION

CONCEPT

A word familiar to all fans of science fiction, *mutation* refers to any sudden change in DNA—deoxyribonucleic acid, the genetic blueprint for an organism—that creates a change in an organism's appearance, behavior, or health. Unlike in the sci-fi movies, however, scientists typically use the word mutant as an adjective rather than as a noun, as, for example, in the phrase "a mutant strain." Mutation is a phenomenon significant to many aspects of life on Earth and is one of the principal means by which evolutionary change takes place. It is also the cause of numerous conditions, ranging from albinism to cystic fibrosis to dwarfism. Mutation indicates a response to an outside factor, and the nature of that factor can vary greatly, from environmental influences to drugsto high-energy radiation.

HOW IT WORKS

DNA, Chromosomes, and Mutations

Deoxyribonucleic acid, or DNA, is a molecule in the cells of all life-forms that contains genetic codes for inheritance. DNA, discussed elsewhere in this book, is as complex in structure as it is critically important in shaping the characteristics of the organism to which it belongs, and therefore it is not surprising that a subtle alteration in DNA can produce significant results. Alterations to DNA are called mutations, and they can result in the formation of new characteristics that are heritable, or capable of being inherited.

Every cell in the body of every living organism contains DNA in threadlike structures called chromosomes. Stretches of DNA that hold coded instructions for the manufacture of specific proteins are known as genes, of which the human race has approximately 40,000 varieties. If the DNA of a particular gene is altered, that gene may become defective, and the protein for which it codes also may be missing or defective. Just one missing or abnormal protein can have an enormous effect on the entire body: albinism, for instance, is the result of one missing protein.

Mutations also can be errors in all or part of a chromosome. Humans normally have 23 pairs of chromosomes, and an extra chromosome can have a tremendous negative impact. For example, there should be two of chromosome 21, as with all other chromosomes, but if there are three, the result is Down syndrome. People with Down syndrome have a unique physical appearance and are developmentally disabled. Nor is an extra chromosome the only chromosomal abnormality that causes problems: if chromosomes 9 and 22 exchange materials, a phenomenon known as *translocation,* the result can be a certain type of leukemia. Down syndrome also results from translocation.

Germinal mutations are those that occur in the egg or sperm cells and therefore can be passed on to the organism's offspring. Somatic mutations are those that happen in cells other than the sex cells, and they cannot be transmitted to the next generation. This is an important distinction to keep in mind in terms of both the causes and the effects of mutation. If only the somatic cells of the organism are affected, the mutation will not appear in the next generation; on the other hand, if a germinal mutation is involved, what was once an abnormality may

become so common in certain populations that it emerges as the norm.

The Role of Mutation in Evolution

Most of the forms of mutation we discuss in this essay appear suddenly (i.e., in a single generation) and affect just a few generations. Yet even such seemingly "normal" characteristics as our ten fingers and ten toes or our two eyes or our relatively hairless skin (compared with that of apes) are ultimately the product of mutations that took shape over the many hundreds of millions of years during which animal life has been evolving. Evolution, in fact, is driven by mutation, along with natural selection (see Evolution).

Over the eons, advantageous mutations, examples of which we look at later, have allowed life to develop and diversify from primitive cells into the multitude of species—including *Homo sapiens*—that exist on Earth today. If DNA replicated perfectly every time, without errors, the only life-forms existing now would be those that existed about three billion years ago: single-cell organisms. Mutations, therefore, are critical to the development of diverse life-forms, a phenomenon known as *speciation* (see Speciation). Mutations that allow an organism to survive and reproduce better than other members of its species are always beneficial, though a mutation that may be beneficial in some circumstances can be harmful in others. Mutations become especially important when an organism's environment is changing—something that has happened often over the course of evolutionary history. And though we cannot watch evolution taking place, we can see how mutations are used among domesticated plants and animals, as discussed later.

REAL-LIFE APPLICATIONS

Ethnicity and Mutation

Every single human trait—blue eyes, red hair, cystic fibrosis, a second toe longer than the big toe, and so on—is the result of some genetic mutation somewhere back down the line. Traits that are shared by all people must have arisen long ago, while other traits occur only in certain populations of people. Traits may be as innocuous as eye color or hair texture or as grave as a shared tendency toward a particular disease. Cystic fibrosis, for instance, is most common in people of northern European descent, while sickle cell anemia (see Amino Acids) occurs frequently in those of African and Mediterranean ancestry. A fatal disorder known as Tay-Sachs is found primarily in Jewish people whose ancestors came from Eastern Europe. In many cases, the particular mutation, while harmful in one regard, proved to be a useful one for that population. We know, for example, that while two copies of the mutant sickle cell anemia gene cause illness, one copy confers resistance to malaria—a very useful trait to people living in the tropics, where malaria is common.

THE PIMA "FAT-STORAGE MUTATION." Researchers have noted a high incidence of obesity among the Pima, a Native American tribe whose ancestral homeland is along the Gila and Salt rivers in Arizona. The Pima tend to eat a diet that is no more fatty than that of the average American—which, of course, means that it is plenty fatty, complete with chips, bologna, ice cream, and all the other high-calorie, low-nutrient foods that most Americans consume. But whereas the average American is overweight, the average Pima is more dramatically so. This suggests that long ago, when the ancestors of the Pima had to face repeated periods of famine in the dry lands of the American Southwest, survival favored the individual or individuals who had a mutation for fat storage. It so happens that today, there is more than enough food at the local supermarket, but by now the Pima as a group has the fat-storage gene. Therefore, many members of the tribe have to undergo strict dietary and exercise regimens so as not to become grossly overweight and susceptible to heart disease and other ailments.

Favorable Mutations

As with other mutations relating to ethnic groups, scientists have hypothesized that some advantage must be conferred upon people with single copies of the cystic fibrosis gene or the Tay-Sachs disease gene. Though many mutations are harmful, others prove to be beneficial to a species by helping it adapt to a particular environmental influence. Useful mutations, in fact, are the driving force behind evolution.

The processes of evolution are usually much too slow for people to discern, but it is possible to



Pygmies, a group of people in southern Africa, appear to be midgets through a germinal mutation, but in most populations the mutation is somatic, occurring only occasionally in families whose other members are of ordinary size. *(© Bettmann/Corbis. Reproduced by permission.)*

observe the effects of selective breeding when applied to domesticated animals and plants. The artificial selection of pigeons by breeders, in fact, provided the English naturalist Charles Darwin (1809–1882) with a model for his theory of natural selection, discussed in Evolution. Likewise, animal and plant breeders use mutations to produce new or improved strains of crops and livestock. Careful breeding in this manner has spawned the many different breeds of dogs, cats, and horses—each with their characteristic coloring, size, temperament, and so on—that we know today. It also has resulted in crops that are resistant to drought or insects or which have a high yield per acre. Likewise, goldfish, yellow roses, and Concord grapes are all descendants of ancestors with specific mutations.

Diseases and Mutation

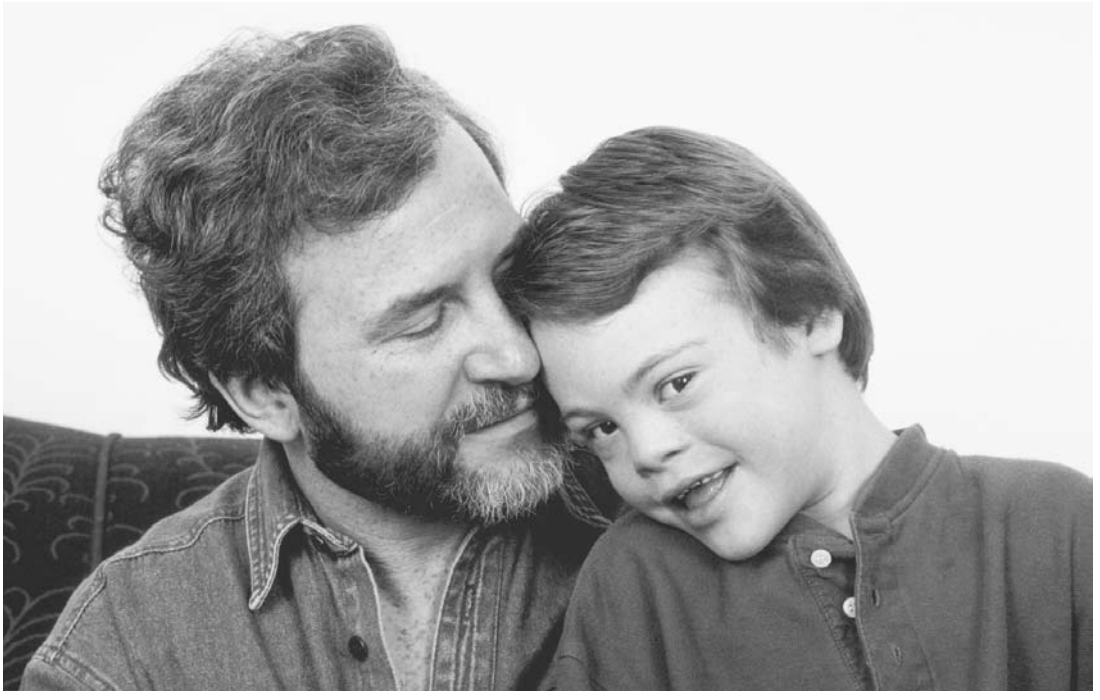
The majority of mutations, however, are less than favorable, and this is illustrated by the relationship between mutation and certain hereditary diseases. An example is Huntington disease, a condition that strikes people in their forties or fifties and slowly disables their nervous systems. It produces shaking and a range of other symptoms, including depression, irritability, and apathy, and is usually fatal. The gene associated with Huntington's is dominant.

The horrible degenerative brain condition known as Creutzfeldt-Jakob disease, discussed in Diseases, is usually caused by another mutation. (Though it can be caused by infection, most cases of the disease are the result of heredity.) As with some of the other conditions we have mentioned, this one seems to affect particular groups more than others. Whereas the worldwide incidence of this rare condition is about one in one million, among Libyan Jews the rate is higher. The disease is a type of spongiform encephalopathy, so named because it produces characteristic spongelike patterns on the surface of the brain. Spongiform encephalopathies are caused by the appearance of a prion, a deviant form of protein whose production typically is caused by a mutation.

Most hereditary diseases are, by definition, linked with a mutation. Such is the case with hemophilia, for instance (see Noninfectious Diseases), and with cystic fibrosis, a lethal disorder that clogs the lungs with mucus and typically kills the patient before the age of 30 years. Cystic fibrosis, like Huntington, occurs when a person inherits two copies of a mutated gene. In 1989 researchers found the source of cystic fibrosis on chromosome 7, where an infinitesimal change in the DNA sequence leads to the production of an aberrant protein.

Congenital Disorders

In the past, all manner of superstitions arose to explain why a child was born, for instance, with a cleft palate, a situation in which the two sides of the roof of the mouth fail to meet, causing a speech disorder that may be mild or severe. Once known as a *harelip,* the cleft palate was said to have formed as a result of the mother's being frightened by a hare while she was carrying the child. In fact, it is just one example of a congenital disorder, an abnormality of structure or function or a disease that is present at birth. Congenital disorders, which also are called birth defects, may be the result of several different factors, mutation being one of the most significant. Among the many examples of congenital disorder are the hereditary diseases we have already mentioned, as well as dwarfism, Down syn-



AN EXTRA CHROMOSOME 21 CAUSES DOWN SYNDROME. PEOPLE WITH THIS CONGENITAL DISORDER HAVE UNIQUE PHYSICAL FEATURES, SUCH AS A WIDE, FLAT FACE AND SLANTED EYES, AND ARE DEVELOPMENTALLY DISABLED. *(© Laura Dwight/Corbis. Reproduced by permission.)*

drome, albinism, and numerous other conditions.

DWARVES AND MIDGETS. The term *dwarf* has many associations from fairy tales—an example of the combined fascination and revulsion with which people with congenital disorders have long been treated—but it also is used to describe persons of abnormally short stature. A dwarf is distinguished from a midget in a number of ways, all of which indicate that the features of a midget are less removed from the norm. Midgets, while small, have bodies with proportions in the ordinary range. Likewise, the intelligence and sexual development of an adult midget are similar to those of other adults, and a midget or midget couple typically produces children of ordinary size. Pygmies, a group of people in southern Africa, appear to be midgets through a germinal mutation, but in many populations the mutation is somatic, occurring only occasionally in families whose other members are of ordinary size.

Dwarfs, by contrast, have several different disorders. One variety of dwarfism, known in the past as *cretinism,* is characterized by a small, abnormally proportioned body and an impaired mind. On the other hand, several forms of hereditary dwarfism carry with them no ill effect on the mental capacity. For example, people with the type of dwarfism known as *achondroplasia* have short limbs and unusually large heads, but the life span and intelligence of someone with this condition are quite normal. In the case of diastrophic dwarfism, the brain is fine, but the skeleton is deformed, and the risk of death from respiratory failure is high in infancy. Persons with diastrophic dwarfism who survive early childhood, however, are likely to enjoy a normal life span.

DOWN SYNDROME. Like people with many other congenital disorders, those with Down syndrome used to be called by a name that now is considered crude and insensitive: *mongoloid.* The term, when used with a capital *M,* refers to people of east Asian descent and is analogous to other broad racial groupings: Caucasoid, Negroid, and Australoid. In the case of people with Down syndrome, *mongoloid* referred to the unusual facial features that mark someone with that condition.

A person with Down syndrome (caused by an extra chromosome in the 21st chromosomal pair) is likely to have a wide, flat face and eyes that are slanted, sometimes with what is known



An albino northern fur seal. A condition that results from an inherited defect in melanin metabolism (melanin is responsible for the coloring of skin), albinism is marked by an absence of pigment from the hair, skin, and eyes. *(© John Francis/Corbis. Reproduced by permission.)*

as an *inner epicanthal fold*—all facial characteristics common among people who are racially Mongoloid. Numerous other facial features identify a person with Down syndrome as someone who suffers from a specific congenital disorder, including a short neck, ears that are set low, a small nose, large tongue and lips, and a chin that slopes. People with Down syndrome are apt to have poor muscle tone and possess abnormal ridge patterns on their palms and fingers and the soles of their feet. Heart and kidney problems are common with Down syndrome as well, but one feature is most common of all: mental retardation. The condition occurs in about one of 1,000 live births among women under age 40 but about one in 40 live births to older women. Overall, the incidence is about one in 800 live births. As noted earlier, the cause of Down syndrome is translocation, but the reason translocation occurs is not known.

ALBINISM. Compared with dwarfism or Down syndrome, albinism is not nearly as severe in terms of its effect on a person's functioning. A condition that results from an inherited defect in melanin metabolism (melanin is responsible for the coloring of skin), albinism is marked by an absence of pigment from the hair, skin, and eyes. The hair of an albino tends to be whitish blond, the skin an extremely pale white, and the eyes pinkish. Albinism occurs among other animals: hence the white rats, rabbits, and mice almost everyone has seen. Domestic white chickens, geese, and horses are partial albinos that retain pigment in their eyes, legs, and feet. As was once true of people with other congenital disorders, human albinos once inspired fear and awe. Sometimes they were killed at birth, and in the mid–nineteenth century, albinos were exhibited in carnival sideshows. In these cruel spectacles, sometimes whole families were put on display, touted as a unique race of "night people" who lived underground and came out only when the light was dim enough not to hurt their eyes.

On the other hand, some ethnic groups experience enough albino births that another one causes no excitement. For example, among the San Blas Indians of Panama, one in approximately 130 births is an albino, compared with one in 17,000 for humans as a whole. Albinism comes about when melanocytes (melanin-producing cells) fail to produce melanin. In tyrosinase-negative albinism, the most common form, the enzyme tyrosinase (a catalyst in the conversion of tyrosine to melanin) is missing from the

KEY TERMS

AMINO ACIDS: Organic compounds made of carbon, hydrogen, oxygen, nitrogen, and (in some cases) sulfur bonded in characteristic formations. Strings of amino acids make up proteins.

CHROMOSOME: DNA-containing bodies, located in the cells of most living things, that hold most of the organism's genes.

CONGENITAL DISORDER: An abnormality of structure or function or a disease that is present at birth. Congenital disorders also are called *birth defects.*

DNA: Deoxyribonucleic acid, a molecule in all cells, and many viruses, containing genetic codes for inheritance.

GENE: A unit of information about a particular heritable trait. Usually stored on chromosomes, genes contain specifications for the structure of a particular polypeptide or protein.

GERMINAL MUTATION: A mutation that occurs in the egg or sperm cells, which therefore can be passed on to the organism's offspring.

HERITABLE: Capable of being inherited.

MUTAGEN: A chemical or physical factor that increases the rate of mutation.

MUTATION: Alteration in the physical structure of an organism's DNA, resulting in a genetic change that can be inherited.

NATURAL SELECTION: The process whereby some organisms thrive and others perish, depending on their degree of adaptation to a particular environment.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to compounds containing carbon and hydrogen.

POLYPEPTIDE: A group of between 10 and 50 amino acids.

PROTEINS: Large molecules built from long chains of 50 or more amino acids. Proteins serve the functions of promoting normal growth, repairing damaged tissue, contributing to the body's immune system, and making enzymes.

RNA: Ribonucleic acid, the molecule translated from DNA in the cell nucleus, the control center of the cell, that directs protein synthesis in the cytoplasm, or the space between cells.

SOMATIC MUTATION: A mutation that occurs in cells other than the reproductive, or sex, cells. These mutations, as contrasted with germinal mutations, cannot be transmitted to the next generation.

SPECIATION: The divergence of evolutionary lineages and creation of new species.

TRANSLOCATION: A mutation in which chromosomes exchange parts.

melanocytes. When the enzyme is missing, no melanin is produced. In tyrosinase-positive albinism, a defect in the body's tyrosine transport system impairs melanin production. One in every 34,000 persons in the United States has tyrosinase-negative albinism. It is equally common among blacks and whites, while more blacks than whites are affected by tyrosinase-positive albinism. Native Americans have a particularly high incidence of both forms of albinism.

Mutagens and Other Causes

As might be expected, cells that divide many, many times in a lifetime are more at risk of errors and mutations than cells that divide less frequently. In a human female, egg cells are fully formed at birth, and they never divide thereafter. By contrast, sperm cells are being produced constantly, and the older a man is, the more frequently his sperm-producing cells have divided. By age 20 they will have divided 200 times and by age 45 about 770 times. This has led scientists to hypothesize that when a baby is born with a congenital disorder caused by an error in cell division, the father is the parent more likely to have contributed the gene with the mutation.

This is just one example of why mutation occurs. Many mutations are caused by mutagens—chemical or physical factors that increase the rate of mutation. Some mutagens occur naturally, and some are synthetic. Cosmic rays from space, for instance, are natural, but they are mutagenic. Some naturally occurring viruses are considered mutagenic, since they can insert themselves into host DNA. Hydrogen and atomic bombs are man-made, and they emit harmful radiation, which is a mutagen. Recreational drugs, tobacco, and alcohol also can be mutagens in the bodies of pregnant women. The first mutagens to be identified were carcinogens, or cancer-causing substances. Carcinogens in chimney soot were linked with the chimney sweep's cancer of late eighteenth-century England, discussed in Noninfectious Diseases. In fact, cancer itself is a kind of mutation, involving uncontrolled cell growth. Other environmental factors that are known to bring about mutations include exposure to pesticides, asbestos, and some food additives, many of which have been banned.

Where to Learn More

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REPRODUCTION AND BIRTH

REPRODUCTION
SEXUAL REPRODUCTION
PREGNANCY AND BIRTH

REPRODUCTION

CONCEPT

The term reproduction encompasses the entire variety of means by which plants and animals produce offspring. Reproductive processes fall into two broad groupings: sexual and asexual, the latter being the means by which bacteria and algae reproduce. Many plants reproduce sexually by means of pollination, and some plants alternate between sexual and asexual forms of reproduction. Other creatures, such as bees and ants, reproduce through a form of reproduction called parthenogenesis, which is neither fully sexual nor asexual.

HOW IT WORKS

Asexual Reproduction

Asexual reproduction involves only one organism, as opposed to two in sexual reproduction. It occurs when a single cell divides to form two daughter cells that are genetically identical to the parent cell. This process is known as fission, and it may take the form either of binary fission, in which two new cells are produced, or multiple fission, which results in the creation of many new cells. Since there is no fusion of two different cells, the daughter cells produced by asexual reproduction are genetically identical to the parent cell. Asexual reproduction usually takes place by mitosis, a process during which the chromosomes in a cell's nucleus are duplicated before cell division. (Mitosis, chromosomes, and many other topics referred to in this essay are discussed in considerably more detail in Genetics.)

Whereas sexual reproduction is extremely complex—and human sexual reproduction is much more so, freighted as it is with degrees of meaning that go far beyond mere biology—asexual reproduction is a fairly simple, cellular process. Of course, nothing in nature is really simple, and, in fact, the dividing and replication of DNA (deoxyribonucleic acid, the genetic blueprint material found in each cell) is a complicated subject; however, that subject, too, is discussed in the essay Genetics. DNA is located at the cell nucleus, which is the cell's control center, and the nucleus is the first part of the cell to divide in asexual reproduction. After the nucleus splits, the cytoplasm, or the cellular material external to the nucleus, then divides. The result is the formation of two new daughter cells whose nuclei have the same number and kind of chromosomes as the parent.

The adaptive advantage of asexual reproduction is that organisms can reproduce quickly and by doing so colonize favorable environments rapidly. (See Evolution for more about the importance of adaptation and environment in shaping species.) For example, some bacteria can double their numbers every 20 minutes. In addition to bacteria, which are discussed in more detail in Infection, other life-forms that reproduce asexually include protozoa (varieties of which are examined in Parasites and Parasitology), blue-green algae, yeast, dandelions, and flatworms.

Sexual Reproduction

Sexual reproduction involves the union of two organisms rather than the splitting of one. Like asexual reproduction, it is a process that takes place at the cellular level. In sexual reproduction it is not binary fission that occurs, but the fusion of two cells. Nor are the two cells identical;

rather, the cells—known as gametes—can be identified as either male or female according to the makeup of their chromosomes. The male gamete is called a sperm cell, and the female gamete is termed an egg cell. In sexual reproduction, the sperm cell fuses, or bonds, with the egg cell to produce a cell that is genetically different from either of the parent cells. This process of fusion is known as fertilization, and the fertilized egg is called a zygote. Gametes are produced in the male testes and female ovaries by a splitting process called meiosis. (Meiosis and other terms mentioned briefly in these paragraphs are discussed in much more detail in Genetics.)

Meiosis produces haploid cells, or ones that have half the number of chromosomes as are in a normal cell for that species. When the haploid sperm and egg cells fuse at fertilization, however, the chromosomes from both combine, so that the normal number of chromosomes appears in the zygote. The shuffling of the parents' genetic material that happens during meiosis allows for new gene combinations in offspring that account for variations between offspring (which is why you don't look just like your siblings) and which, over time, can improve a species' chances of survival.

REAL-LIFE APPLICATIONS

Examples of Asexual Reproduction

As we noted earlier, bacteria, blue-green algae, most protozoa, yeast, and flatworms all reproduce asexually, as do mosses and starfish. (The last actually reproduce both sexually and asexually by means of alternation of generations, discussed later.) The products of asexual reproduction are known as clones—an example of the fact, discussed in Genetic Engineering, that cloning and the concept of clones are not as new as one might imagine. (See that essay for much more about artificial cloning.) A starfish can regenerate and eventually produce a whole new organism from a single severed appendage, while flatworms divide in two and regenerate to form two new flatworms. This formation of a separate organism is obviously much more complex than the simple splitting of single bacteria cells, but it is still a form of asexual reproduction.

VEGETATIVE PROPAGATION. Strawberries reproduce by forming growths called runners, which grow horizontally and generate new stalks. At some point, the runner decomposes, leaving a new plant that is a clone of the original. This is an example of vegetative propagation, a term for a number of processes by which crop plants are produced asexually. Vegetative propagation is used for such crops as potatoes, bananas, raspberries, pineapples, and some flowering plants. Its advantage to farmers is that the crops will be more uniform than those grown from seed. Furthermore, some plants are difficult to cultivate from seed, and the vegetative propagation of those plants makes it possible to grow crops that otherwise would not be available for commercial marketing.

In reproducing potatoes through vegetative propagation, farmers plant the so-called eyes to produce duplicates of the parent. With banana plants, the farmer separates the suckers that grow from the root of the plant and plants them. The farmer raising raspberry bushes bends the branches and covers them with soil, whereupon a process not unlike that of the runner growth of mosses takes place: the branches eventually grow into a separate plant, with their own root system, and ultimately can be detached from the parent plant.

Between Asexual and Sexual

The example of vegetative propagation suggests that there is not a sharp dividing line between sexual and asexual reproduction—that is, that many organisms can reproduce either way. This is true even of humans, who, in theory, could be cloned, though the technology to do so—let alone resolution of the ethical issues of the procedure—lies in the far distant future. (See Genetic Engineering for more on this subject.) Even humans, however, can use external fertilization, which is sexual reproduction without sexual intercourse (see Sexual Reproduction).

Plants go through a process known as alternation of generations, in which they alternate as sexual and asexual reproducers, or gametophytes and sporophytes, respectively. In the asexual stage, the sporophyte produces diploid reproductive cells called spores, which develop into gametophytes. These gametophytes produce haploid gametes, which then unite sexually to form a diploid zygote that grows into a sporophyte. In

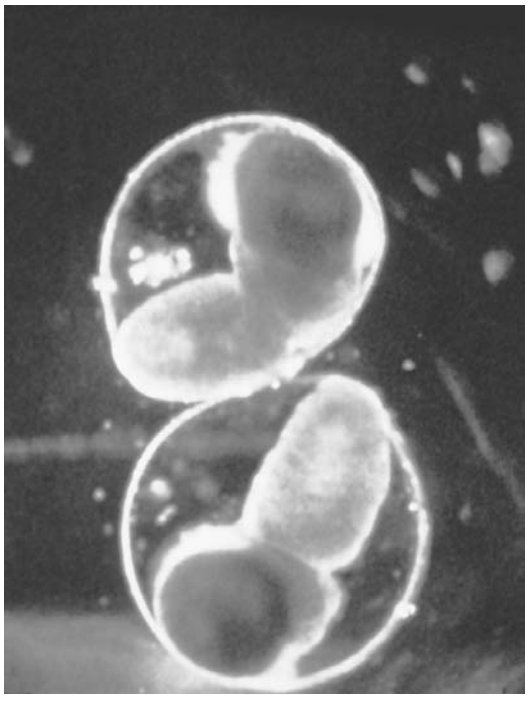


A pineapple top placed on soil can root and develop into a plant. Numerous crop plants, among them, potatoes, bananas, raspberries, and pineapples, are produced asexually, a process called vegetative propagation. *(© Corbis. Reproduced by permission.)*

plain English, this means that the asexual "grandparent" generates a sexually reproducing "child," which in turn produces a "grandchild" that is asexual, like its grandparent.

At one phase in the alternation of generation for mosses, for instance, male and female moss plants grow from spores. Male moss plants produce sperm cells, which, when the moss receives rainfall, are able to propagate because they have a medium (water) in which to move. They fertilize the female plants, producing zygotes. The zygote grows on top of the female moss plant, which helps to store moisture and thus provides a hospitable environment in which the zygote can develop. The zygote eventually produces haploid spores, which it releases into the air. These tiny spores, carried by the wind, float away from their point of origin until they come to rest, and soon the cycle begins once again.

PARTHENOGENESIS. There are also organisms, including bees, ants, wasps, and other insects, that reproduce in a way that is neither fully sexual nor asexual. This is parthenogenesis, a type of reproduction in which a gamete develops without fertilization. In other words, a sex cell is reproduced without actual intercourse between male and female. The gamete is almost always female—a fact indicated in the name itself, which comes from *parthenos,* Greek for "maiden."



The acorn worm undergoes asexual reproduction by budding; small pieces fragment from the trunk, and each grows into a new worm. *(© Lester V. Bergman/Corbis. Reproduced by permission.)*

The Parthenon in Athens, like the city itself, is named after the goddess Athena (also called Minerva), who was known by the nickname Parthenos. She is said to have been born fully formed, having sprung from the head of her father, Zeus, dressed in armor and ready for battle. Thus, her own birth was a form of parthenogenesis, a word whose second half (a name well known from the Bible) means "beginning."

Pollen and Pollination

Pollen is a fine, powdery substance consisting of microscopic grains containing the male gametophyte of certain plants that reproduce sexually. These plants include angiosperms, a type of plant that produces flowers during sexual reproduction, and gymnosperms, which reproduce sexually through the use of seeds that are exposed and not hidden in an ovary, as with an angiosperm. Pollen is designed for long-distance dispersal from the parent plant, so that fertilization can occur. Pollination is the transfer of pollen from the male reproductive organs to the female reproductive organs of a plant, and it precedes fertilization. In other words, pollination is the equivalent of sexual intercourse for seed-bearing plants. Actually, cross-pollination, or the transfer of pollen from one plant to another, would perhaps be analogous to sexual intercourse in animals. Pollination occurs in seed-bearing plants, as opposed to the more primitive spore-producing plants, such as ferns and mosses. Gymnosperms, such as pines, firs, and spruces, produce male and female cones, whereas angiosperms produce flowers containing a male organ called the stamen and a female organ called the pistil. Both types of plants rely on insects and other creatures to aid in the pollen transfer.

Darwin's moth. The German physician and botanist Rudolf Jakob Camerarius (1665–1721) was the first scientist to demonstrate that plants reproduce sexually, and he pioneered the study of pollination. One of the scientists influenced by his work was the English naturalist Charles Darwin (1809–1882), who discussed the subject in *The Various Contrivances by which Orchids Are Fertilized by Insects* (1862). Darwin wrote this book partly to support the ideas on evolution presented in his much more well known book *Origin of Species* (1859). In *Various Contrivances,* he suggested that orchids and their insect pollinators evolved by interacting with one another over many generations.

As an example, he discussed *Angraecum sesquipedale,* an orchid native to Madagascar. Darwin had not seen the plant in its native habitat, however; he had looked only at its dried leaves. The white flower of this orchid has a foot-long (30 cm) tubular spur with a small drop of nectar at its base, and from observing this, he hypothesized that the orchid had been pollinated by an insect with a foot-long tongue. This hypothesis, he wrote, "has been ridiculed by some entomologists," or scientists who study insects. After all, no such creature had been found in Madagascar. But then, around the turn of the nineteenth century—some two decades after Darwin's death—it was found. A Madagascan moth was discovered that had a foot-long tongue that uncoils to sip the nectar of *A. sesquipedale* as it cross-pollinated the flowers.

Plants and their pollinators. Angiosperms and gymnosperms are discussed in Ecosystems and Ecology, where each is compared in terms of its degree of adaptation to its environment. Angiosperms seem to be the hands-down winner: by enlisting the aid of

KEY TERMS

ALTERNATION OF GENERATIONS: A process whereby plant generations alternate as sexual and asexual reproducers—gametophytes and sporophytes, respectively.

ASEXUAL REPRODUCTION: One of the two major varieties of reproduction (along with sexual reproduction), In contrast to sexual reproduction, which involves two organisms, asexual reproduction involves only one. Asexual reproduction occurs when a single cell divides through mitosis to form two daughter cells, which are genetically identical to the parent cell.

BINARY FISSION: The process in asexual reproduction whereby a single cell divides to form two daughter cells that are genetically identical to the parent cell.

CLONE: A cell, group of cells, or organism that contains genetic information identical to that of its parent cell or organism.

CLONING: A specialized genetic process whereby clones are produced. Cloning is a form of asexual reproduction.

CHROMOSOME: A DNA-containing body, located in the cells of most living things, that holds most of the organism's genes.

CROSS-POLLINATION: The transfer of pollen from one plant to another.

CYTOPLASM: The material inside a cell that is external to the nucleus.

DIPLOID: A term for a cell that has the basic number of doubled chromosomes.

DNA: Deoxyribonucleic acid, a molecule in all cells, and many viruses, that contains genetic codes for inheritance.

EGG CELL: A female gamete.

ENZYME: A protein material that speeds up chemical reactions in the bodies of plants and animals without itself taking part in or being consumed by those reactions.

FERTILIZATION: The process of cellular fusion that takes place in sexual reproduction. The nucleus of a male reproductive cell, or gamete, fuses with the nucleus of a female gamete to produce a zygote.

GAMETE: A reproductive cell—that is, a mature male or female germ cell that possesses a haploid set of chromosomes and is prepared to form a new diploid by undergoing fusion with a haploid gamete of the opposite sex. Sperm and egg cells are, respectively, male and female gametes.

GAMETOPHYTE: In alternation of generations, a gametophyte is a plant that reproduces sexually.

GERM CELL: One of two basic types of cells in a multicellular organism. In contrast to somatic or body cells, germ cells play a part in reproduction.

HAPLOID: A term for a cell that has half the number of chromosomes that appear in a diploid or somatic cell.

MEIOSIS: The process of cell division that produces haploid genetic material. Compare with *mitosis.*

MITOSIS: A process of cell division that produces diploid cells, as in asexual reproduction. Compare with *meiosis.*

NUCLEUS: The control center of a cell, where DNA is stored.

OVARY: Female reproductive organ that contains the eggs.

KEY TERMS CONTINUED

OVULE: Female haploid gametophyte of seed plants, which develops into a seed upon fertilization by a pollen grain.

PARTHENOGENESIS: A type of reproduction that involves the development of a gamete without fertilization. In other words, a sex cell (usually female) is reproduced without actual intercourse between male and female.

POLLEN: Male haploid gametophyte of seed plants (including angiosperms and gymnosperms), which unites with the ovule to form a seed. Pollen is a fine, powdery substance consisting of microscopic grains.

POLLINATION: The transfer of pollen from the male reproductive organs to the female reproductive organs of a plant. Pollination precedes fertilization. See also *cross-pollination.*

REGENERATION: A biological process among some lower animals whereby a severed body part is restored by the growth of a new one.

SEXUAL REPRODUCTION: One of the two major varieties of reproduction (along with asexual reproduction). In contrast to asexual reproduction, which involves a single organism, sexual reproduction involves two. Sexual reproduction occurs when male and female gametes undergo fusion, a process known as fertilization, and produce cells that are genetically different from those of either parent.

SOMATIC CELL: One of two basic types of cells in a multicellular organism. In contrast to germ cells, somatic cells (also known as body cells) are not involved in reproduction; rather, they make up the tissues, organs, and other parts of the organism.

SPERM CELL: A male gamete.

SPOROPHYTE: In alternation of generations, a sporophyte is a plant that reproduces asexually.

ZYGOTE: A diploid cell formed by the fusion of two gametes.

insects and other pollinators, they manage to pollinate much more efficiently than gymnosperms, which have to produce vast quantities of pollen for each grain that reaches its target. Typically, pollination benefits the animal pollinator by supplying it with sweet nectar and, of course, benefits the plant by providing direct transfer of pollen from one plant to the pistil of another plant. For this reason, specific plant and animal species have developed a relationship of mutualism, a form of symbiosis in which each participant reaps benefits (see Symbiosis). In many cases, plant and pollinator have evolved together, and it is possible to determine which animal pollinates a certain flower species simply by studying the morphologic features (shapes), color, and odor of the flower.

For example, some flowers are pure red, or nearly pure red, and have very little odor. In most such situations, the pollinator is a bird species, since birds have excellent vision in the red region of the spectrum but a rather undeveloped sense of smell. It so happens that Europe, which has no pure red native flowers, also has no bird-pollinated native flower species. Not all bird-pollinated flowers are red, but they are all characterized by striking, and sometimes contrasting, colors that readily catch the eye. Examples of plants pollinated by birds include the cardinal flower, the red columbine, the hibiscus, the eucalyptus, and varieties of orchid, cactus, and pineapple.

Some flowering plants have a very strong odor but are very dark, or at least drab, in color.

These flowers and plants—examples include the saguaro cactus, century plant, or cup-and-saucer vine—are often pollinated by bats, which have very poor vision, are typically active during the night, and have a very well developed sense of smell. The flowers of many plant species are marked with special pigments called flavonoids, which absorb ultraviolet light and appear to direct the pollinator toward the pollen and nectar. These pigments are invisible to humans and most animals, but bees' eyes have special ultraviolet photoreceptors that enable the bees to detect patterns and so pollinate these flowers.

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SEXUAL REPRODUCTION

CONCEPT

Sexual reproduction is one of the two major ways, along with asexual reproduction, that plants and animals create offspring and thus propagate the species. Critical to sexual reproduction is the process of fertilization, whereby the male and female sex cells fuse, or bond. Fertilization may be of two types, either internal or external, and though humans normally fertilize by the first of those means, they may use the second, in the form of *in vitro* fertilization. Humans, of course, have by far the most complicated reproductive process, inasmuch as it is surrounded by a vast societal, interpersonal, and moral framework that is not a factor in animal reproduction. Part of that framework is the activity that precedes sexual reproduction: attraction, courtship, and so forth. Although no other animal's courtship rituals rival those of humans for sophistication, some of them are quite impressive in their complexity.

HOW IT WORKS

The Reproductive System

The contrast between sexual and asexual reproduction is examined in Reproduction, an essay that also provides examples of plant reproduction through pollination. The present essay is concerned primarily with human sexual reproduction and secondarily with animal sexual reproduction. Some technical aspects of reproduction at the cellular level require consultation of processes explained in Genetics; here we confine our technical discussion to reproduction at the level of organs, fluids, and other bodily components. Reproduction is facilitated by the reproductive system, a group of organized structures that can be subdivided into male and female reproductive systems. During puberty, which typically occurs between the ages of 10 and 14 years, the reproductive systems of both sexes mature. This phase is marked in part by the release of eggs (female sex cells) in the female ovary and the formation of sperm (male sex cells) in the male testes. Reproduction can take place only when a sperm unites with an egg, a process called *fertilization.*

THE MALE REPRODUCTIVE SYSTEM. The testes are the pair of male reproductive glands located in the scrotum, a skin-covered sac that hangs from the groin. Each testis produces sperm cells, while the testes as a whole secrete testosterone. Testosterone is a hormone—a type of molecule that sends signals to spots remote from its point of origin to induce specific effects on the activities of other cells. Testosterone is associated with masculinity, though females secrete it in much smaller quantities as well. In males, testosterone secretion is critical to the development of secondary sexual characteristics—those unique traits that mark a person as a male or female, though they do not occur in the sexual organs themselves. A deepened voice is an example of a male secondary sex characteristic evident at puberty.

Sperm cells produced in the testes move to the epididymis, a coiled tube at the base of the penis where they are stored and matured. During ejaculation, or the ejection of sperm from the penis during orgasm, sperm travel from the epididymis through a long tube called the *vas deferens* to the urethra. This single tube, which extends from the bladder to the tip of the penis, is also the means by which urine passes out of the

body. Liquid secretions from various glands combine with sperm (itself a gooey substance that is barely liquid) to form the semen, or seminal fluid. Ejaculated semen may contain as many as 400 million sperm.

The Female Reproductive System

The female system is much more complicated than the male version and has a role in all stages of reproduction. Whereas the male system primarily delivers semen to the vagina, the female system plays a critical part from fertilization until long after the birth of offspring. It produces ova, or eggs, receives sperm from the penis, houses and provides nutrients to the developing zygote (fertilized egg) and later the embryo and fetus, gives birth to offspring, and feeds those offspring after birth.

The visible part of the female reproductive system, which, of course, is not even half of the entire picture, includes the opening of the vagina and the external genital organs, or vulva. The vagina, a muscular tube extending from the uterus to the outside of the body, is the receptacle for sperm ejaculated during sexual intercourse and also forms part of the birth canal that will be used later, when the offspring comes to term. The external genital organs, known collectively as the *vulva,* include the labia, folds of skin on both sides of the openings to the vagina and urethra; the clitoris, a small, sensitive organ that is comparable to the male penis inasmuch as it swells when stimulated; and the mons pubis, a mound of fatty tissue above the clitoris.

The ovaries and menstruation. Eggs are produced in the ovaries, oval-shaped organs in the groin that also generate sex hormones. At birth, a female's ovaries contain hundreds of thousands of undeveloped eggs, each surrounded by a group of cells to form a follicle, or sac; however, only about 360-480 follicles reach full maturity. During puberty the action of hormones causes several follicles to develop each month. Normally, just one follicle fully matures, rupturing and releasing an ovum through the ovary wall in a process called *ovulation.* The mature egg enters one of the paired fallopian tubes, where it may be fertilized by a sperm and move on to the uterus to develop into a fetus. The lining of the uterus, called the *endometrium,* prepares for pregnancy each month by thickening, but if fertilization does not take place, the endometrium is shed during menstruation.

Fertilization

During sexual intercourse, a man releases approximately 300 million sperm into a woman's vagina, but only one of the sperm can fertilize the ovum. The successful sperm cell must enter the uterus, swim up the fallopian tube (a trumpet-shaped passageway between the ovary and the uterus) to meet the ovum, and then pass through a thick coating, known as the *zona pellucida,* that surrounds the egg. The head of the sperm cell contains enzymes (a type of protein that speeds up chemical reactions—see Enzymes) that break through the zona pellucida and allow the sperm to penetrate the egg. Once the head of the sperm is inside the egg, the tail falls off, and the outside of the egg thickens to prevent another sperm from entering. Many variables affect whether fertilization occurs after intercourse among humans. One factor is a woman's ovulatory, or menstrual, cycle. Human eggs can be fertilized for only a few days after ovulation, which typically occurs only once every 28 days. (To learn about what happens after fertilization, see Pregnancy and Birth.)

REAL-LIFE APPLICATIONS

External Fertilization

Most land animals use some form of internal fertilization similar to that which we have described for humans. External fertilization, on the other hand, is more common among aquatic animals, who simply dump their sperm and eggs into the water and let currents mix the two male and female cells together. The sea urchin is a typical example: a male sea urchin releases several billion sperm into the water, and these sperm then swim toward eggs released in the same area. Fertilization occurs within seconds when sperm come into contact and fuse with eggs. As noted in Reproduction, external fertilization is essentially sexual reproduction without sexual intercourse. For humans the process of reproduction by external means may lack the intimacy of internal reproduction, but since 1978 a form of external fertilization has offered the opportunity of con-



During in vitro fertilization, eggs are removed surgically from a female's reproductive tract and fertilized in a test tube or petri dish with sperm (shown here). After the fertilized eggs have divided twice and an embryo is starting to form, they are reintroduced to the female's body. *(© Owen Franken/Corbis. Reproduced by permission.)*

ceiving children to couples who otherwise might have remained childless.

In vitro Fertilization. This form of external fertilization is known as *in vitro,* or "in glass"—that is, in a glass test tube or petri dish. The term is contrasted with *in vivo,* meaning "in a living organism," or *in utero,* "in the uterus." During *in vitro* fertilization, eggs are removed surgically from a female's reproductive tract. They then can be fertilized in a test tube or petri dish by sperm taken from the woman's partner or another male. After the fertilized eggs have divided twice, indicating that the operation has "taken" and an embryo is starting to form, they are reintroduced to the female's body. If all goes well, the embryo and fetus eventually result in a normal birth.

In vitro fertilization has been performed successfully on a variety of domestic animals since the 1950s but on humans only since the late 1970s. Two English physicians, Patrick Steptoe (1913–1988) and Robert G. Edwards (1925–), developed a method for stimulating ovulation with hormone treatment and then retrieving the nearly mature eggs and placing them in a petri dish to mature. In their breakthrough 1978 operation, they added male sperm to the egg in the petri dish, where fertilization took place, and then implanted the eight-celled embryo in the mother's body. The result of this extraordinary operation was a healthy baby named Louise Brown.

A world without sex? The birth of Louise, whose twentieth birthday was celebrated in Britain with great fanfare, excited fears and controversy similar to those surrounding cloning (see Genetic Engineering). As with cloning, the fear was that the technology of *in vitro* fertilization would lead to the depersonalized manufacturing of human beings associated with some nightmarish future society, but this has not come to pass for several reasons. One is that *in vitro* fertilization is successful only about 15% of the time. Another, much more significant reason is that there are few women capable of producing a child through internal fertilization who would want to conceive without the intimacy of sexual intercourse.

There are exceptions, of course, in real life (two women in a same-sex relationship who want a child, for example) as well as in fiction. In the latter category, the character of Jenny Fields

in the American novelist John Irving's *World According to Garp*—published, ironically, in the same year as the birth of Louise Brown—would undoubtedly have conceived a child by *in vitro* means if those means had been available to her. As it was, Jenny, who conceived the book's title character during World War II, manages to do so by having intercourse purely for the purpose of producing offspring. She does this by choosing a wounded, brain-damaged airman who will never remember having had sex with her and who dies shortly thereafter.

Courtship

There is something far greater than mere biochemistry involved in sexual reproduction, which is why humans enjoy the intimacy of producing a baby. This is also why courtship and mating rituals are a significant part of human life, providing a means by which a male and female join as partners. Such is true even in modern America and the West in general, where the aftermath of the 1960s sexual revolution has left behind a world largely stripped of its former mystery. For better or worse, sex before marriage is a common part of life today in a way that it was not before the 1960s, with the advent of birth control and "free love," and today there is little stigma attached to the conception of a child outside wedlock. That much has changed—and changed dramatically—but humans still practice courtship.

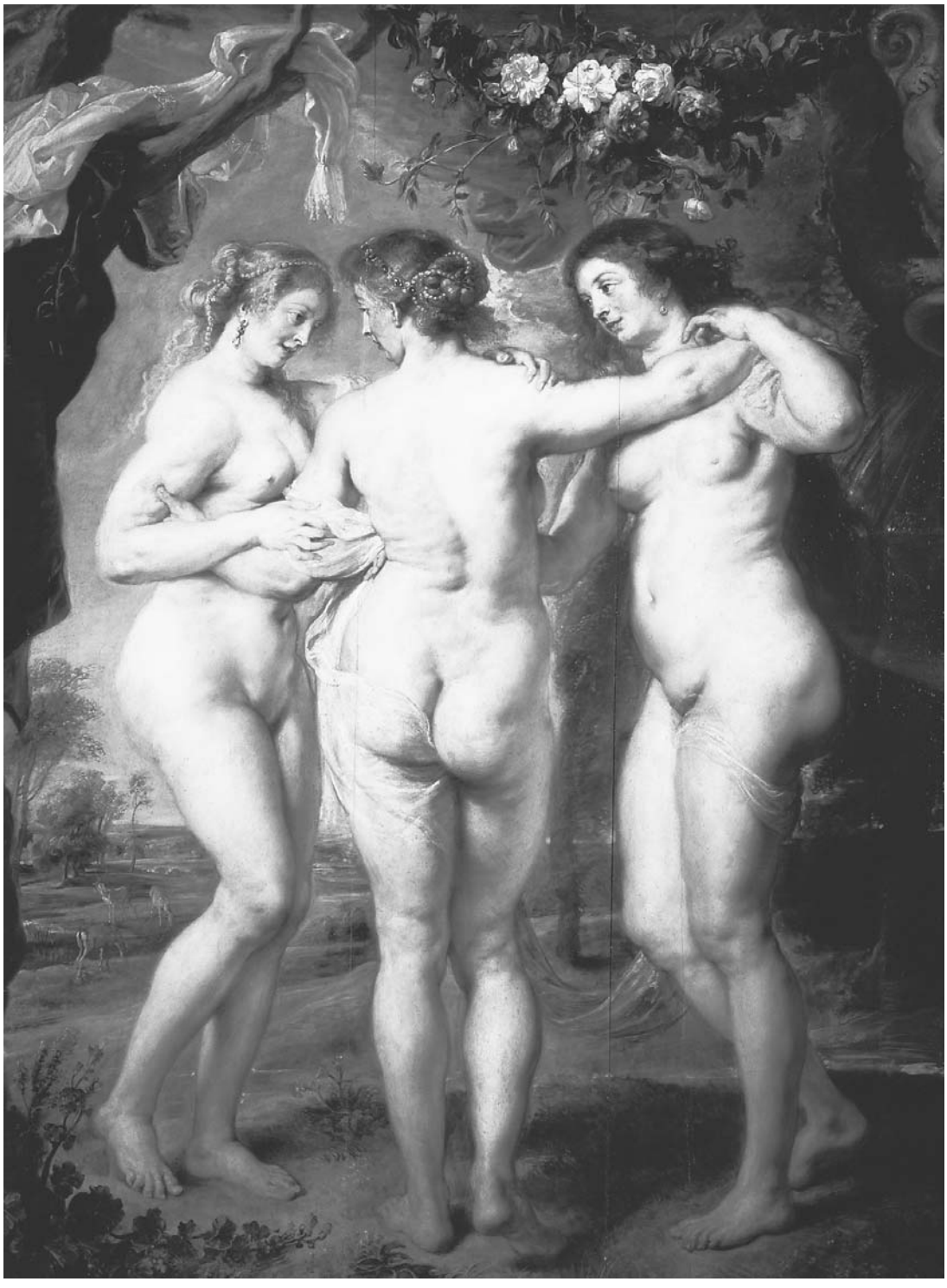
Males still have to prove to females that they are suitable mates, usually by displaying their physical prowess or some other attribute associated with masculinity. Females still do most of the choosing, and despite all the changes in views toward male and female roles, the ideas of basic male and female differences seem to be hardwired into the minds of most people. This is particularly so of people who are heterosexual and especially those who either have children or intend to have them. Such attitudes are not surprising, since humans, while being something more than animals, are still animals as well.

Animal courtship. Among animals, courtship is a complex set of behaviors that leads to mating. Courtship behavior communicates to each potential mate that the other is not a threat and serves to reveal to each that the species, gender, and physical condition of the other are suitable for mating. During courtship, animals use rituals, a series of behaviors for communication that is performed the same way by all the males or females in a species. They are governed by fixed-action patterns (FAPs), which are virtually identical with instinct (see Instinct and Learning). In courtship, some animals leap and dance, others sing, and still others ruffle their feathers or puff up pouches. The male peacock displays his glorious plumage to the female, and humpback whales advertise their presence under the sea by singing a song that can be heard hundreds of miles away. Courtship behavior enables an animal to find, identify, attract, and arouse a mate. Animals use signals, such as the release of pheromones, or scent signals, as well as visual displays to claim a particular mate or a territory.



Among animals, courtship is a complex set of behaviors that leads to mating. Here male frigate birds display their inflated scarlet pouches to attract females. *(© Wolfgang Kaehler/Corbis. Reproduced by permission.)*

Choosing a mate. Usually, the females do the choosing. In some species of birds, males display themselves in a small communal area called a *lek,* where females select a mate from the parading males. Across the animal kingdom, males generally compete with one another for mates, either by fighting or by ritualized displays, and females pick the best quality of



"The Three Graces" by Peter Paul Rubens. A more amply formed female body is an ideal much closer to nature, since our evolutionary lineage has tended to favor women with large hips who are capable of bearing many children. *(© Archivo Iconografico, S.A./Corbis. Reproduced by permission.)*

male available. Several basic factors influence a female in her choice of mate. First, she wants a male who can provide for her offspring, which is why the female tern (a type of bird) selects a good fish catcher. As part of courtship among common terns, the male birds display fish to the females and may even feed them to the females as a way of demonstrating their ability to feed

young. Among the long-jawed long-horned beetles that live in the Arizona desert, males battle each other for saguaro cactus fruit, and the females mate in exchange for access to the fruit.

Genetic fitness, or the ability to survive—and to advance the survival of the species—is another important factor in mate selection. This is a large part of the reason why males may fight each other for a female—to show her that they are the most fit. Of course, the female animal does not know that she is choosing on this basis, but she is, and she is likely to select a partner with a striking appearance, capable of energetic displays—both of which are signs of good health.

Secondary Sex Characteristics, Evolution, and the Model of an Ideal Mate

Humans, too, have deeply ingrained ideas regarding what makes an attractive potential mate, though to some extent, those ideas are cultural. Most societies regard a muscular male as attractive, for obvious evolutionary reasons: a physically fit male can provide for his mate and offspring, both by acquiring food and other resources and by protecting the nest. On the other hand, the modern American ideal of feminine beauty is more removed from nature. For one thing, this image of an attractive female is a thin body but large breasts—two things that seldom go together in nature but which are possible in the modern world through breast implantation surgery. That is, the achievement of such an ideal is available to a woman with a naturally thin body who also possesses the financial resources (and, of course, the desire) to undergo such surgery.

A woman naturally gifted with large breasts is apt also to have large buttocks, hips, and thighs, and while some men may find such anatomical features (particularly the first) desirable, this more natural version of the female body is not the image usually promoted in advertising or other media. Therefore, if a woman with a full figure wishes to meet societal expectations regarding beauty, she must endure something much more strenuous than a mere operation—a strict low-fat diet and a great deal of exercise. Given these often unnatural expectations from society, it is no wonder that a great many women express frustration with their attempts to conform to them, nor is it any wonder that many women in the modern world simply stop trying to conform. In any case, the American ideal of a thin female is far from universal, in terms of either place or time. Many traditional cultures favor a more amply formed female body, as did Western civilization in the past—a fact exemplified by the paintings of seventeenth-century artists, such as Peter Paul Rubens, famous for his fleshy female subjects. This is an ideal much closer to nature, since our evolutionary lineage has tended to favor women with large hips who are capable of bearing many children.

Evolution and the sensitive man. As with much else about sexual reproduction and the courtship rituals associated with it, the idea of beauty—itself an expression of secondary sex characteristics—is much simpler for men. As we noted earlier, physical fitness in men almost always is regarded as attractive, but women often value men for other traits, most notably intelligence and sense of humor. Whereas many men place an emphasis on physical appearance in choosing a mate, women's expectations are much more complex and they are also likely to be much more forgiving toward members of the male population who do not look like Tom Cruise or some other Hollywood image of attractiveness.

In defense of modern men, many have complained that modern women do not always want what they say they want. For example, from the early 1970s onward, it often was said in public discussions of sexuality on TV or in magazines that women wanted men to be more sensitive. That is, they wanted men who were more verbal and given to talking about their feelings and who were more aware of the woman and her needs. It is not surprising that men were failing to meet these expectations, since the idea of the "strong, silent type" is a masculine ideal in many cultures. Furthermore, not only civilization but also evolution has tended to favor men who are given more to actions than to words—men who can make war, either on the battlefield or in the business world.

Such aggressive characteristics are all well and good among animals or in a human society just struggling to survive. But in the modern West, where most material needs are easily met, women have sought and expressed a desire for something more from men. Such was the situation that emerged in the wake of the sexual revolution, when people became more open not only

KEY TERMS

CHROMOSOME: A DNA-containing body, located in the cells of most living things, that holds most of the organism's genes.

DIPLOID: A term for a cell that has the basic number of doubled chromosomes.

EGG CELL: A female gamete.

EMBRYO: The stage of animal development in the uterus before the animal is considered a fetus. In humans this is equivalent to the first three months.

FALLOPIAN TUBES: A set of trumpet-like tubes that carries a fertilized egg from the ovary to the uterus.

FAPS: Fixed-action patterns of behavior, or strong responses on the part of an animal to particular stimuli. *FAP* is virtually synonymous with *instinct.*

FERTILIZATION: The process of cellular fusion that takes place in sexual reproduction. The nucleus of a male reproductive cell, or gamete, fuses with the nucleus of an female gamete to produce a zygote.

FETUS: An unborn or unhatched vertebrate that has taken on the shape typical of its kind. An unborn human usually is called a *fetus* during the period from three months after fertilization to the time of birth.

GAMETE: A reproductive cell—that is, a mature male or female germ cell that possesses a haploid set of chromosomes and is prepared to form a new diploid by undergoing fusion with a haploid gamete of the opposite sex. Sperm and egg cells are, respectively, male and female gametes.

GENITALIA: The sex organs, which include the male penis and the female vagina.

GESTATION: The period between fertilization and birth during which the unborn offspring develops in the uterus.

HAPLOID: A term for a cell that has half the number of chromosomes that appear in a diploid or somatic cell.

HORMONE: Molecules produced by living cells, which send signals to spots remote from their point of origin and induce specific effects on the activities of other cells.

about sex itself but about their feelings as well. Although the sexual revolution yielded a number of negative effects, including the loss of mystery associated with sex and an increase in out-of-wedlock pregnancies and cases of sexually transmitted disease, it also made it possible for people to be frank in a way that they had never been before. One outgrowth of this was the revelation, in many women's magazines, that women were no longer satisfied or impressed with strong, silent men.

During the 1970s the model of the sensitive man emerged, and for the first time it became possible for men to talk about their feelings. And they did, in books, in movies such as those of Woody Allen, and in therapist-led encounter groups or men's groups. Gradually, however, a surprising fact emerged: women did not want men to be *too* sensitive and certainly not too nonmasculine. They wanted a man who would talk about his feelings but not a man who wore his heart on his sleeve. They wanted to be treated as equals in the workplace, but if there was a strange noise in the house at night, they wanted the man to go see what it was. They wanted a man who would respect them—but not a man who was so polite and predictable that he possessed no air of mystery.

KEY TERMS CONTINUED

MENSTRUATION: Sloughing off of the lining of the uterus, which occurs monthly in nonpregnant females who have not reached menopause (the point at which menstrual cycles cease) and which is manifested as a discharge of blood.

OVARY: Female reproductive organ that contains the eggs.

OVUM: An egg cell.

PUBERTY: A stage in the maturation of humans and higher primates wherein the person first becomes capable of sexual reproduction. It is marked by the development of secondary sex characteristics, the maturation of the genital organs, and the beginning of menstruation in females. Puberty typically takes place somewhere between the ages of about 10 and 14 years.

SECONDARY SEX CHARACTERISTICS: Those unique traits that mark an individual as a male or female but which are not manifested in the sexual organs themselves. Facial hair and a deep voice in males or breast development as well as hip and buttocks development in females are examples.

SEXUAL REPRODUCTION: One of the two major varieties of reproduction, along with asexual reproduction. In contrast to asexual reproduction, which involves a single organism, sexual reproduction involves two. Sexual reproduction occurs when male and female gametes undergo fusion, a process known as *fertilization,* and produce cells that are genetically different from those of either parent.

SPERM CELL: A male gamete.

TESTES: The pair of male reproductive glands located in the scrotum, a skin-covered sac that hangs from the groin.

UTERUS: A reproductive organ, found in most female mammals, in which an embryo and later a fetus grow and develop.

VAGINA: A passage from the uterus to the outside of the body.

ZYGOTE: A diploid cell formed by the fusion of two gametes.

All of this reveals a great deal about humans and sexual reproduction. First of all, mating, or the interaction between males and females, is about far more than reproduction or even sex. It is an interaction that involves the whole person. Second, human sexuality is surrounded by webs of psychological, social, and spiritual complexity that make it a phenomenon quite different from animal sexuality, which tends to be about little more than procreation. And, third, for all the progress humans have made, and for all the levels of civilization that separate us from our evolutionary roots, there is still something in human sexuality that responds to very basic ideas about sex, the sexes, and the need to propagate the species through mating and reproduction.

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PREGNANCY AND BIRTH

CONCEPT

One of the greatest dramas in the world of living things is that which takes place in pregnancy and birth. Pregnancy forms a bond between mother and offspring that, in humans at least, lasts throughout life. Humans and many other animals are viviparous, meaning that offspring develop inside the mother's body and are delivered live. By contrast, birds and some other varieties of animal are oviparous, meaning that they deliver offspring in eggs that must develop further before hatching. In the modern world, human females experience birth in several ways—vaginal or cesarean, with anesthetics and without, at home or in a hospital—but just a few hundred years ago, there was little variety in an experience that was almost always painful and dangerous.

HOW IT WORKS

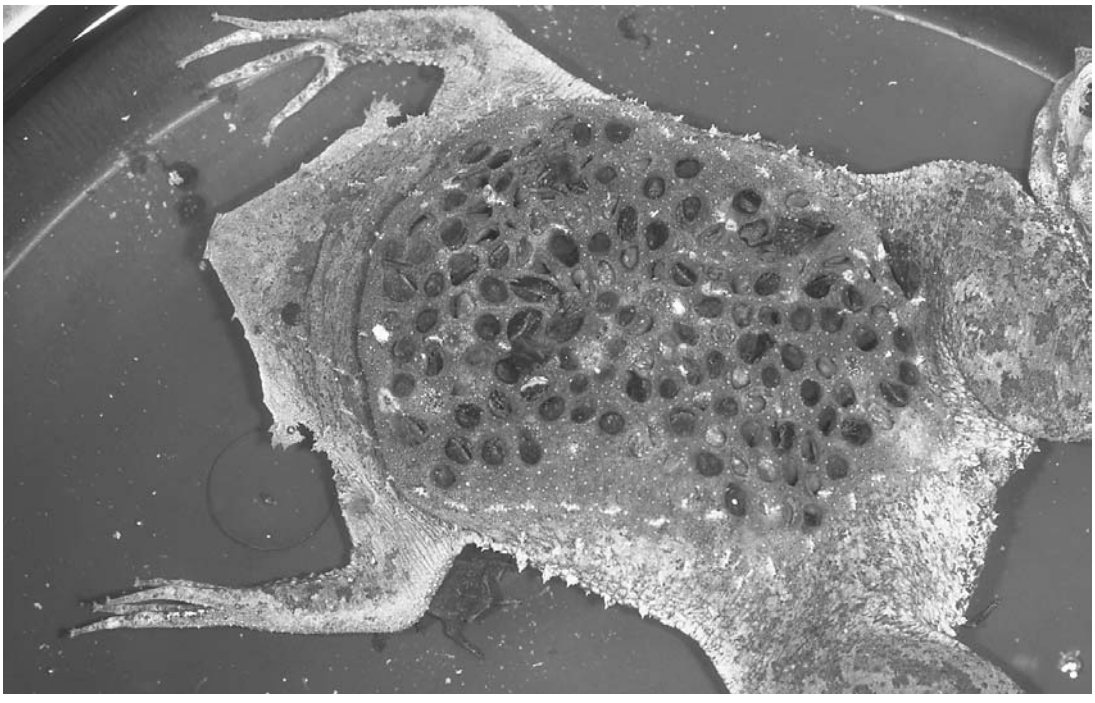
Oviparity, Viviparity, and Ovoviviparity

The birth of live offspring is a reproductive feature shared by mammals, some fishes, and selected invertebrates, such as scorpions, as well as various reptiles and amphibians. Animals who give birth to live offspring are called viviparous, meaning "live birth." In contrast to viviparous animals, other animals—called oviparous, meaning "egg birth"—give birth to eggs that must develop before hatching. Finally, there are ovoviviparous animals, or ones that produce eggs but retain them inside the female body until hatching occurs, so that "live" offspring are born.

Oviparous animals may fertilize their eggs either externally or internally, though all animals that fertilize their eggs externally in nature are oviparous. (See Sexual Reproduction for more about internal and external fertilization.) In cases of internal fertilization, male animals somehow pass their sperm into the female: for example, male salamanders deposit a sperm packet, or spermatophore, onto the bottom of their breeding pond and then induce an egg-bearing (or gravid) female to walk over it. The female picks up the spermatophore and retains it inside her body, where the eggs become fertilized. These fertilized eggs later are laid and develop externally. Oviparous offspring undergoing development before birth obtain all their nourishment from the yolk and the protein-rich albumen, or "white," rather than from direct contact with the mother.

Ovoviviparity is common in a wide range of animals, including certain insects, fish, lizards, and snakes, but it is much less typical than oviparity. Ovoviviparous insects do not supply oxygen or nourishment to their developing eggs; they merely give them a safe brooding chamber for development. Nonetheless, species of ovoviviparous fish, lizards, and snakes appear to provide some nutrition and oxygen to their growing offspring. Because nutrition is provided in these instances, some zoologists consider them examples of true live birth, or viviparity.

VIVIPARITY. Viviparity is the type of birth process that takes place in most mammals and many other species. Viviparous animals give birth to living young that have been nourished in close contact with their mothers' bodies. The offspring of both viviparous and oviparous animals develop from fertilized eggs, but the eggs of viviparous



Oviparous animals give birth to eggs that must develop before hatching. The Surinam toad, for example, carries her eggs attached to her back while they mature. *(© David A. Northcott/Corbis. Reproduced by permission.)*

animals lack a hard outer covering, or shell. Viviparous young grow in the adult female until they are able to survive on their own outside her body. In many cases, the developing fetuses of viviparous animals are connected to a placenta, a special membranous organ with a rich blood supply that lines the uterus in pregnant mammals. It provides nourishment to the fetus through a supply line called an umbilical cord.

All mammals, except for the platypus and the echidnas, are viviparous; only these two unusual mammals, called montremes, lay eggs. (See Speciation for more about mammal species.) Some snakes, such as the garter snake, are viviparous, as are certain lizards and even a few insects. Ocean perch, some sharks, and a few popular aquarium fish are also viviparous. Even certain plants, such as the mangrove and the tiger lily, are described as viviparous because they produce seeds that germinate, or sprout, before they become detached from the parent plant.

From Zygote to Fetus

The essays on Reproduction and Sexual Reproduction discuss the basics of the reproductive process through the point of fertilization. A fertilized egg is called a zygote, but once it begins to develop in the uterus or womb, it is known as an embryo and later, when it begins to assume the shape typical of its species, a fetus. In the uterus, the unborn offspring receives nutrients and oxygen during the period known as gestation, which extends from fertilization to birth. (In humans the gestation period is nine months.)

The zygote forms in one of the mother's fallopian tubes, the tubes that connect the ovaries with the uterus. It then travels to the uterus, where it becomes affixed to the uterine lining. Along the way, the zygote divides a number of times, such that by the time it reaches the uterus it consists of about 100 cells and is called an embryoblast. The exact day on which the embryoblast implants on the uterine wall varies, but it is usually about the sixth day after fertilization. By the end of the first week, a protective sac, known as the amniotic cavity, begins to form around the embryoblast.

Embryo and fetus. Changes then begin to take place at a rapid rate. As each week passes, the embryo takes on more and more necessary and distinctive features, such as blood vessels in week 3, internal organs in week 5, and finger and thumb buds on the hands in week 7. Unfortunately, miscarriages are not uncommon in the early weeks of pregnancy. The mother's immune system (see Immune System) may react

to cells from the embryo that it classifies as "foreign" and begin to attack those cells. The embryo may die and be expelled. The first three months of embryonic development are known as the first trimester, or the first three-month period of growth. At the end of the first trimester, the embryo is about 3 in. (7.5 cm) long and looks like a tiny version of an adult human. Thereafter, the growing organism is no longer an embryo, but a fetus. Fetal development continues through the second and third trimesters until the baby is ready for birth at the end of ninth months.

PREPARING FOR BIRTH

At the end of the gestation period, the mother's uterus begins to contract rhythmically, a process called labor. This is accompanied by the release of hormones, most notably oxytocin. From the time of fertilization, quantities of the hormone progesterone, which keeps the uterus from contracting, are high; but during the last weeks of gestation, maternal progesterone levels begin to drop, while levels of the female hormone estrogen rise. When progesterone levels drop to very low levels and estrogen levels are highest, the uterus begins to contract.

Meanwhile, as birth approaches, the brain's pituitary gland releases oxytocin, a hormone that stimulates uterine contractions and controls the production of milk in the mammary glands (a process called lactation). Synthetic oxytocin sometimes is given to women to induce labor. Scientists believe that the pressure of the fetus's head against the cervix, the opening of the uterus, ultimately initiates the secretion of oxytocin. As the fetus's head presses against the cervix, the uterus stretches and relays a message along nerves to the pituitary gland, which responds by releasing oxytocin. The more the uterus stretches, the more oxytocin is released.

LABOR AND DELIVERY. Rhythmic contractions dilate the cervix, causing the fetus to move down the birth canal and to be expelled together with the placenta, which has supplied the developing fetus with nutrients from the mother during the gestation period. Before delivery, the placenta separates from the wall of the uterus. Since the placenta contains many blood vessels, its separation from the wall of the uterus causes bleeding. This bleeding is normal, assuming that it is not excessive. After the placenta separates from the uterine wall, it moves into the birth canal and is expelled from the vagina. The uterus continues to contract even after the placenta is delivered, and it is thought that these contractions serve to control bleeding.

After the baby is born, the umbilical cord that has attached the fetus to the placenta is clamped. The clamping cuts off the circulation of the cord, which eventually stops pulsing owing to the interruption of its blood supply. The baby now must breathe air through its own lungs, whereas before it has been breathing, fishlike, in the warm, wet environment of the mother's amniotic fluid. The process of labor described here in a very cursory fashion (it is actually much more complicated) can take from less than one hour to 48 hours, but typically the entire birth process takes about 16 hours.

REAL-LIFE APPLICATIONS

CHANGING VIEWS ON CHILDBIRTH

Before modern times, the realm of childbirth was a world exclusive to women, and few men ever entered the birth chamber. It was a place of excruciating pain and serious danger to the mother giving birth, so filled with blood and screaming that few men would have dared enter even if they had wanted to do so. Women had to give birth without anesthesia and any number of other amenities of modern medical care, including sophisticated diagnostic techniques and equipment, such as ultrasound, as well as antiseptic environments and surgical techniques, such as cesarean section.

In those days, birthing assistance was the work of midwives, women who lacked formal schooling in medicine (which was unavailable to most women in any case) but made up in experience for what they lacked in education. By about 1500, however, as medicine began to progress after many centuries of stagnation, male doctors increasingly forced midwives out of a job. In 1540 the European Guild of Surgeons declared that "no carpenter, smith, weaver, or woman shall practice surgery." A major turning point in the male takeover of birthing assistance duties came with the invention of the forceps, tong-like instruments that could be used for extracting a baby during difficult births. The inventor was the

English obstetrician (a physician concerned with childbirth) Peter Chamberlen the Elder (1560–1631), and he and his descendants for a century closely guarded the design of the brilliant invention. Even the mothers on whom it was used never saw the instrument, and midwives were prohibited from using forceps to assist during childbirth.

OBSTETRICIANS TAKE OVER. By the eighteenth century, however, Chamberlen's descendants had released their exclusive claim over the forceps, and use of the instrument spread to other medical professionals. This gave male obstetricians a great technological advantage over female midwives and further ensured the separation of the midwives from the medical profession. By 1750 numerous physicians and surgeons had gained the status of "man-midwives," and the growth of university courses on obstetrics established it as a distinct medical specialty. By the latter part of the 1700s, most women of the upper classes had come to rely on professionally trained doctors rather than midwives, yet in America, where doctors were scarcer than in Europe, the profession of midwife continued to flourish into the 1800s. Still, by the early twentieth century, childbirth had moved out of the home and into the hospital, and at mid-century it had become a completely medical process, attended by physicians and managed with medical equipment and procedures, such as fetal monitors, anesthesia, and surgical interventions.

THE REACTION IN THE LATE TWENTIETH CENTURY. Many women of the late twentieth century found themselves dissatisfied with this clinical approach to childbirth. Some believed that the medical establishment had taken control of a natural biological process, and women who wanted more command over labor and delivery helped popularize new ideas on childbirth that sought to reduce or eliminate medical interventions. Today, some women choose to deliver with the help of a nurse-midwife, who, like her premodern counterparts, is trained to deliver babies but is not a doctor. There are women who even choose home birth, attended by a doctor or midwife or sometimes both. There are even brave souls who, in the face of increasing concern about the effect of anesthesia on the fetus, refuse artificial means of controlling pain and instead rely on breathing and relaxation techniques. For the first time in many years, the screams of women giving birth "naturally" once again filled the halls of hospital maternity wards and home birthing rooms.

Modern Childbirth

The last few paragraphs represent an extreme reaction—a view not shared by many women, who have been more than happy to avail themselves of the benefits of childbirth in the modern world. Such benefits include an epidural, a type of anesthetic procedure that serves to alleviate the pain of parturition, or childbirth, while making it possible for the mother to remain conscious. Still, even for women who have no interest in giving birth at home or without the aid of drugs, much has changed in the world of childbirth. Women may choose a happy medium between the medical establishment and more traditional methods, for instance, by opting to consult with an obstetrician *and* a midwife.

Today, many obstetricians are women. This has had an incalculable effect on making childbirth psychologically easier for many women: though some are happy to retain a male obstetrician, many others find themselves much more comfortable being cared for by a physician who, in all likelihood, has given birth herself. The increasingly important role of the female obstetrician, along with other factors, serves to symbolize the fact that the world has progressed beyond the old false dilemma between medical care from a male or a female, between medicine and nature, between hospital and home.

A HOSPITAL AS HOME. Hospital rooms, in fact, are starting to resemble rooms at home. Everywhere one looks in the modern maternity environment, there is evidence that much has changed, not only from the very old days, when male doctors were not involved in childbirth at all, but also from the more recent past, when males took over the process entirely. In a brilliant innovation, many hospitals have created a situation in which the woman gives birth in her own hospital room, which is outfitted with couches, cabinets, curtains, and rocking chairs to make it look like a home rather than a hospital. To emphasize the smooth transition between home life and the delivery room, fathers, once banished from the labor and delivery chambers, now are welcomed as partners in the birth process.



Ultrasound image of a 30-week-old fetus. By the eighteenth week of pregnancy, ultrasound technology can detect many structural abnormalities, such as spina bifida, heart and kidney defects, and harelip. *(© BSIP/Kretz Technik/Photo Researchers. Reproduced by permission.)*

A father may even cut the umbilical cord, and he is certainly likely to be in the delivery room with a video camera, recording the event for posterity—yet another change from the past. Fathers are not the only ones filming in the delivery room. Today, cable television networks, such as the Learning Channel, provide programming that offers a frank view of the delivery process, complete with candid footage that sometimes can be as dramatic as it is revealing. The maternity ward, once a closed place, has increasingly become an open book.

Saving and Improving Lives

Many a mother and father alike can breathe a prayer (or at least a sigh) of thanks for all the innovations that today make birth much safer than it once was. Among them are a variety of techniques for embryo and fetal diagnosis, which help make parents aware of possible problems in the growing embryo. Ultrasound diagnosis, a technique similar to that applied on submarines for locating underwater structures, uses high-pitched sounds that cannot be heard by the human ear. These sounds are bounced off the embryo, and the echoes received are used to identify embryonic size.

By the eighteenth week of pregnancy, ultrasound technology can detect many structural abnormalities, such as spina bifida (various defects of the spine), hydrocephaly (water on the brain), anencephaly (no brain), heart and kidney defects, and harelip (in which the upper lip is divided into two or more parts). On a less dire and much more pleasant note, it can also give future parents an opportunity to gain their first glimpse of their child, and an experienced ultrasound technician usually can tell them the baby's sex if they choose to learn it before the birth.

Prenatal testing. Chorionic villi sampling is the most sophisticated modern technique used to assess possible inherited genetic defects. This test typically is performed between the sixth and eighth week of embryonic development. During the test, a narrow tube is passed through the vagina or the abdomen, and a sample of the chorionic villi (small hairlike projections on the covering of the embryonic sac) is removed while the physician views the baby via ultrasound.

Chorionic villi are rich in both embryonic and maternal blood cells. By studying them, genetic counselors can determine whether the baby will have any of several defects, including

KEY TERMS

EMBRYO: The stage of animal development in the uterus before the point at which the animal is considered a fetus. In humans this is equivalent to the first three months.

FALLOPIAN TUBES: A set of trumpet-like tubes that carries a fertilized egg from the ovary to the uterus.

FERTILIZATION: The process of cellular fusion that takes place in sexual reproduction. The nucleus of a male reproductive cell, or gamete, fuses with the nucleus of a female gamete to produce a zygote.

FETUS: An unborn or unhatched vertebrate that has taken on the shape typical of its kind. An unborn human usually is called a fetus during the period from three months after fertilization to the time of birth.

GESTATION: The time between fertilization and birth, during which the unborn offspring develops in the uterus.

HORMONE: Molecules produced by living cells, which send signals to spots remote from their point of origin and induce specific effects on the activities of other cells.

OVARY: Female reproductive organ that contains the eggs.

OVIPAROUS: A term for an animal that gives birth to eggs that must develop before hatching. Compare with *viviparous.*

OVOVIVIPAROUS: A term for an animal that produces eggs but retains them inside the body until hatching occurs, so that "live" offspring are born. Compare with *oviparous* and *viviparous.*

OVUM: An egg cell.

UTERUS: A reproductive organ, found in most female mammals, in which an embryo and, later, a fetus grows and develops.

VAGINA: A passage from the uterus to the outside of the body.

VIVIPAROUS: A term for an animal that gives birth to live offspring. Compare with *oviparous.*

Down syndrome (characterized by mental retardation, short stature, and a broadened face), cystic fibrosis (which affects the digestive and respiratory systems), and the blood diseases hemophilia, sickle cell anemia, and thalassemia. (Several of these disorders are discussed in different essays throughout this book; for instance, Down syndrome is examined in Mutation.) As with ultrasound, it also can show the baby's gender.

Another important form of prenatal (before the birth of the child) testing is amniocentesis, performed around week 16, in which amniotic fluid is drawn from the uterus by means of a needle inserted through the abdomen. Amniocentesis, too, can reveal the sex of the child, as well as a host of genetic disorders such as Tay-Sachs disease, cystic fibrosis, and Down syndrome. However, amniocentesis involves the risk of fetal loss as a result of disruption of the placenta. Chorionic villi sampling is even more risky, with an even higher possibility of fetal loss than amniocentesis, probably because it is conducted at an earlier stage.

In alpha-fetoprotein screening, which takes place somewhere between the 16th and 18th weeks, proteins from the amniotic sac and the fetal liver are taken as a means of screening for specific defects. Because of uncertainties involved in interpretation of the results, alpha-fetoprotein screening is not a common procedure.

CESAREAN SECTION. Another extremely important technique that has saved the

life of many babies and mothers is cesarean section. The normal position for a baby in delivery is head first; when a baby is in the breech position, with its bottom first, it poses grave dangers to both the mother and the child. Not only could the baby fail to emerge in time to begin breathing normally, thus running the risk of brain damage, but it also can become stuck, endangering the life of the mother. Today these dangers are overcome by such techniques as turning the baby and by cesarean section, an operation in which the baby is removed via surgery from the mother's abdomen. Cesarean sections may also be performed due to other complications, including fetal and/or maternal distress.

The term cesarean refers to the Roman emperor Julius Caesar (102–44 B.C.), who supposedly was delivered in this fashion. But the story of Caesar's birth is undoubtedly a legend: until the early modern era, cesarean sections were performed only to save a living baby after the mother had died in childbirth. The reason is that cesareans were likely to be fatal to the mother. Only in the late nineteenth century, by which time doctors had come to understand the importance of providing an antiseptic or germ-free environment, did cesarean sections become practical. Today the C-section, as it is called, has become a routine procedure—one that has saved literally hundreds of thousands, perhaps millions, of lives.

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EVOLUTION

EVOLUTION

PALEONTOLOGY

EVOLUTION

CONCEPT

Among the dominant concepts of the modern world in general, and biology in particular, few are as powerful—or as misunderstood—as evolution. Even the name is something of a misnomer, since it almost implies some sort of striving to reach a goal, as though the "purpose" of evolution were to produce the most intelligent species, human beings. In fact, what drives evolution is not a quest for biological greatness but something much more down to earth: the need for organisms to survive in their environments. Closely tied to evolution are two processes, mutation and natural selection. Natural selection is a process whereby survival is related directly to the ability of an organism to fit in with its environment, while mutation involves changes in the genetic instructions encoded in organisms.

Although the English naturalist Charles Darwin (1809–1882) often is regarded as the father of evolutionary theory, he was not the first thinker to suggest the idea of evolution as such; however, by positing natural selection as a mechanism for evolution, he provided by far the most convincing theory of evolutionary biological change up to his time. In the years since Darwin, evolutionary theory has evolved, but the essential idea remains a sound one, and it is a "theory" only in the sense that it is impossible to subject it to all possible tests. The idea that evolution is somehow still open to question is another pervasive misconception, and it often appears hand in hand with the most pervasive misconception of all—that evolution is in some way anti-Christian, anti-religion, or anti-God.

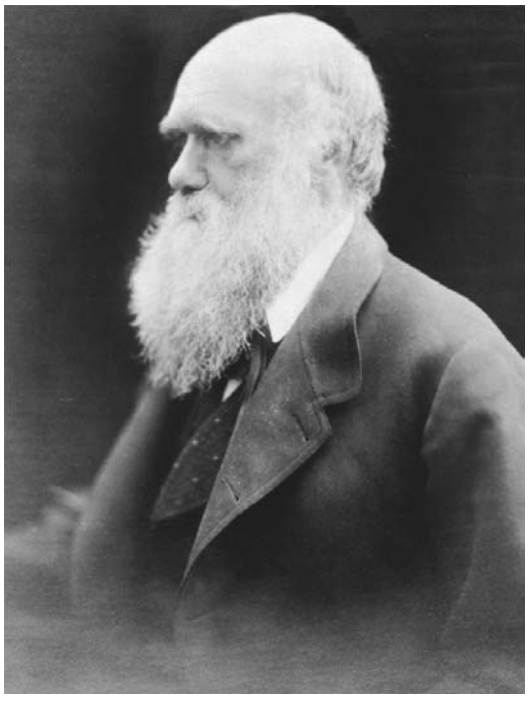
HOW IT WORKS

The "Watch Analogy" and What It (Unintentionally) Teaches About Evolution

Throughout this essay, we discuss misconceptions relating to evolution. Such misconceptions have had such a strong impact on modern civilization that it is important to begin by setting aside a few misguided ideas that strike at the very heart of the evolutionary process. Many of these misconceptions are embodied in a popular "argument" against evolution that goes something like this: Suppose you took a watch apart and laid the pieces on the ground. If you came back in a billion years, would you really expect the watch to have assembled itself?

This argument is a virtual museum of all the fallacies associated with evolution. First of all, a watch (or any of the other variations used in similar arguments) is mechanical, not organic or biological, which is the class of objects under discussion within the framework of evolution. In that sense, the answer to this question is easy enough: No, a watch probably never would assemble itself, because it is not made of living material and it has no need for survival.

Another problem with the watch argument is that it starts with impossibly large pieces. Let us assume that the watch *is* a living being; even so, one would not expect its dials and gears to assemble themselves. But evolution does not make such claims: there is nothing in the theory of evolution to lead one to believe that a collection of organs lying around on a beach eventually would piece themselves together to make a whale.



CHARLES DARWIN *(The Library of Congress.)*

According to what paleontologists (see Paleontology) and other scientists can deduce, over the course of three billion years life-forms evolved from extremely simple self-replicating carbon-based molecules to single-cell organisms. This is hardly what one would call breakneck speed. The more visible or "exciting" part of evolution, with the proliferation of species that produced the dinosaurs and (much later) humans, took place in the past billion years. In fact, the pace of change was still very, very slow until about half a billion years ago, and it has been accelerating ever since. For the vast majority of evolutionary history, however, change has been so slow that, by contrast, watching paint dry would be like playing a high-speed video game.

Ironically, for the watch scenario to be truly analogous to anything in evolution, one would have to start with atoms and molecules not whole gears and dials. Opponents of evolutionary theory might take this fact as being favorable to their cause, but if the watch were made of living, organic material rather than metal, it is possible that the molecules would have some reason to join in the formation of organelles and, later, cells. Or perhaps they would not. Therein lies another problem with the watch analogy and, indeed, with many of the attempts to argue against evolution on a religious basis. This might be called the "fallacy of intention," or the idea that evolution is driven by some overall purpose.

THE "FALLACY OF INTENTION." Hidden in the watch analogy is the idea of the watch itself, the finished product, as a "goal." By the same analogy, the single-cell eukaryotes of a billion or two billion years ago were forming themselves for the purpose of later becoming pine trees or raccoons or people. This is not a valid supposition, as can be illustrated by analogies to human history.

The history of human beings, of course, has taken place over a much, much shorter span than evolutionary history. (The Paleontology essay contains several comparisons between the span of human life on Earth and Earth's entire existence.) Moreover, unlike cells, people *do* form goals and act on intentions, so if there were any good example of change with a goal in mind, it would have to come from human beings. Yet even in the few thousand years that humans have existed in organized societies, most trends have occurred not as part of a major plan but as a means of adapting to conditions.

Consider the situation of a group of nomads who lived in what is now southern Russia about 5,000 years ago. At some point, this vast collection of tribes began to migrate outward, some moving into an area that is now central Asia and the Indian subcontinent and others migrating westward. No sane person would argue that the westward-traveling members of this group knew that in moving to the geographically advantageous territory of Europe, they were putting in place conditions that would help give their descendants dominance over most of the planet some 4,500 years later. Rather, they were probably just trying to find better land for grazing their horses.

We cannot say what the Indo-Europeans, as they are known to history, were looking for. Our only evidence that they existed is the similarities between the languages of Europe, India, and Iran, first noted by the German philologist and folklorist Jacob Grimm (1785–1863) at about the same time that Darwin was formulating his theory of evolution. Grimm, in fact, used methods not unlike those of Darwin, but instead of fossils he studied words and linguistic structures. Along the way, he found remarkable links, such as the Sanskrit word *agni,* cousin to the Latin term *ignis* and such modern English words as *ignite.*

In contrast to the Indo-Europeans, we know a great deal about another group of westward-moving nomads, the Huns of around A.D. 300, who were indeed looking for better grazing lands. Dislocated from their native areas by the building of China's Great Wall, the Huns crossed the Danube River, displacing the Ostrogoths. The Ostrogoths, in turn, moved westward, and this migration set in motion a domino effect that would bring an end to the Western Roman Empire in A.D. 476.

Did the Huns intend to destroy the Roman Empire and bring about the Middle Ages? No reasonable person would adopt such a conspiratorial view of history. Even more absurd, did the Chinese build the Great Wall with the idea of precipitating this entire chain of events? Again, no one would assert such a premise. If those trends in the evolution of societies were not goal-directed, why would we assume that cells and organisms would have to be striving toward a particular end to obtain certain results?

CONFUSING EVOLUTION WITH GOD. In fact, there is no driving "purpose" to evolution—no scientifically based substitute for God operating from behind the scenes and manipulating the evolutionary process to achieve its ultimate aims. Evolution is not guided by any one large aim but by a million or a billion small aims—the need for a particular species of mollusk to survive, for instance.

As we discuss in the course of this essay, the idea of an underlying conflict between evolution and Christianity (or any other religion, for that matter) is almost entirely without merit. On the other hand, it is theoretically possible that all the processes of evolution took place *without* a creator—but this still should not pose a threat to anyone's idea of God.

There is nothing in evolution that would lead to the conclusion that there is no God, that the universe is not God's handiwork, or that God does not continue to engage in a personal relationship with each human. Neither is there anything in evolution that would lead to the conclusion that God *does* exist. Rather, the matter of God is simply not relevant to the questions addressed by evolution. In other words, evolution leaves spiritual belief where it should be (at least, according to Christianity): in the realm of individual choice.

Natural Selection

As we noted earlier, one of the principal mechanisms of evolutionary processes is natural selection. This in itself illustrates the lack of intention, or "goal orientation," in evolution. Like the name *evolution* itself, the term *natural selection* can be deceptive, implying that nature selects certain organisms to survive and condemns others to extinction. In fact, something quite different is at work.

Species tend to overproduce, meaning that the number of field mice, for instance, born in any year is so large that this entire population cannot possibly survive. The reason is that there is never enough of everything—food, water, or living space—for all members of the population to receive what they need. Therefore, only those best adapted to the environment are likely to survive.

FASTER, FURRIER MICE. Suppose, for instance, that the climate in the area where two field mice live is very cold, and suppose that some of the field mice have more protective fur than others; obviously, they are more likely to live. If there are many speedy predators around, judging purely on the basis of that factor alone, it would be easy to predict that the swiftest of the field mice would survive. Thus, faster-running, furrier mice would be "selected" over the slower or less furry mice.

Natural selection is not simply a matter of one particular mouse surviving in an environment. Instead, it involves the survival of specific strains, or lines of descent, that are more suited to the environment in question. Individuals adapted to an environment are more likely to live and reproduce and then pass on their genes to the next generation, while those less adapted are less likely to reproduce and pass on their traits. The genetic strains that survive are not "better" than those that do not—they are only better adapted.

The process of natural selection is ongoing. For example, in generation *A,* the furrier field mice survive and pass on their "furriness" gene to their offspring. Some of the offspring may still not be furry, and these mice will be less likely to survive and reproduce. In addition, since there are almost always several survival factors affecting natural selection, it is likely that other traits also will determine the survivability of certain individual mice and their genes.

For instance, there may be furry but slow mice in generation *B,* which despite their adaptation to temperature conditions are simply not fast enough to get away from predators. Therefore, the mice in generation *C* are likely to be furrier *and* faster than their ancestors. Additional survival factors may come into the picture, to ensure that the average member of generation *D* has sharper teeth in addition to swifter feet and a furrier body.

Although this illustration depicts evolutionary changes as taking place over the course of four generations, they are more likely to occur over the span of 400 or 4,000 or four million generations. In addition, the process is vastly more complicated than it has been portrayed here, because numerous factors are likely to play a part. The essential mechanism outlined here, however, prevails: certain traits are "naturally selected" because individuals possessing those traits are more capable of survival.

THE "SURVIVAL OF THE FITTEST." The concept of natural selection sometimes is rendered popularly as the "survival of the fittest." Scientists are less likely to use this phrase for several reasons, including the fact that it has been associated with distasteful social philosophies or murderous political ideologies—for example, Nazism. Additionally, the word *fittest* is a bit confusing, because it implies "fitness," or the quality of being physically fit.

This implication, in turn, might lead a person to believe that natural selection entails the survival of the *strongest,* which is not the case. Yet this is precisely what proponents of a loosely defined philosophy known as social Darwinism claimed. Popular among a wide range of groups and people in the late nineteenth and early twentieth centuries, social Darwinism could be used in the service of almost any belief. Industrialists and men of wealth asserted that those who succeeded financially did so because they were the fittest, while Marxists claimed that the working class ultimately would triumph for the same reason. Across the political spectrum, social Darwinism confused the meaning of "fittest" with that of other concepts: "strongest," "most advanced," or even "most moral." All of this, it need hardly be said, is misguided, not least because evolutionary theory has nothing to do with race, ethnicity, or social class.

In fact, "survival of the fittest," in a more accurate interpretation, means that individuals that "fit," or "fit in with," their environments are those most likely to survive. This is a far cry from any implication of strength or superiority. Imagine a group of soldiers in combat: Which type of soldier is most likely to survive? Is it the one who scores highest on physical training tests, looks the finest in a uniform, comes from a more socially upper-class home, and has the most advanced education? Or is it the one who keeps his head low, acts prudently, does not rush into dangerous situations without proper reconnaissance, and obeys instruction from qualified leaders?

Clearly, the second set of characteristics has much more to do with survival, even though these qualities may seem less "noble" than the first set. Yet it is by adapting, or proving his or her adaptability, to the environment of war that a soldier survives—not by displays of strength or other types of "fitness" that simply appear impressive. In the same way, the fitness of a species does not necessarily have anything to do with strength: after all, the lion, the "king of beasts," would die out in a polar climate or a desert or an aquatic environment.

Mutation

Although natural selection is of principal importance in evolution, mutation also plays a pivotal role. Mutation is the process whereby changes take place in the genetic blueprint for an organism as a result of alterations in the physical structure of an organism's DNA (deoxyribonucleic acid). DNA is a molecule in all cells and in many viruses that contains genetic codes for inheritance. DNA carries genetic information that is transmitted from parent to offspring; when a mutation occurs, this new genetic information—often quite different from the genetic code received by the parent from the grandparent—is passed on instead.

Under normal conditions of reproduction, a copy of the DNA from the parent is replicated and transmitted to the offspring. The DNA from the parent normally is copied exactly, but every once in a while errors arise during replication. These errors usually originate in noncoding regions of the DNA and therefore have little effect on the observable traits of the offspring. On the other hand, some mutations may be lethal, and thus the offspring does not survive for

the mutation to become apparent. In a very few cases, however, offspring with a slightly modified genetic makeup manage to survive.

CONTRAST WITH ACQUIRED CHARACTERISTICS. Mutation is not to be confused with the inheritance of acquired characteristics, a fallacious doctrine that had its adherents when Darwin was a young man. If acquired characteristics were taken to an extreme, a lumberjack who loses his arm cutting down a tree and later conceives a child with his wife would most likely father a child who is missing an arm. This notion is absurd, and attempts to put forward a workable theory of acquired characteristics in the late eighteenth and early nineteenth centuries involved much greater subtlety. Still, the idea is misguided.

The French natural philosopher Jean Baptiste de Lamarck (1744–1829), one of the leading proponents of acquired characteristics, maintained that giraffes had gained their long necks from the need to stretch and reach leaves at the top of tall trees. In other words, if a giraffe parent had to stretch its neck, a giraffe baby would be born with a stretched neck as well. Later, Darwin's natural selection provided a much more plausible explanation for how the giraffe might have acquired its long neck: assuming that the nutrients it needed were at the highest levels of the local trees, the traits of tallness, long necks, and the ability to stretch would be selected naturally among the giraffe population.

MUTATIONS AND SURVIVAL. Unlike the idea of acquired characteristics, mutation does not entail the inheritance of anatomical traits acquired in the course of an organism's life; rather, it is changes in the DNA that are passed on. For example, when mind-altering drugs became popular among young people in the 1960s, concerns were raised that the offspring of drug takers might suffer birth defects as a result of alterations in their DNA. For the most part, this did not happen. Conditions such as Huntington disease and cystic fibrosis, however, are the result of mutations in DNA; so, too, is albinism, which eliminates skin pigment.

Although mutations often are regarded as undesirable because they can affect the health of individuals adversely, they also can have positive effects for the population in question. Suppose a group of bacteria is exposed to an antibiotic, which rapidly kills off the vast majority of the bacteria. In a fraction of those who survive, however, a mutation may develop that makes them resistant to the medication. Eventually, these mutant bacteria will reproduce, creating more mutants and in time yielding an entire population resistant to the antibiotic.

This is the reason why antibiotics can lose their effectiveness over time: bacteria with mutant genes will render every antibiotic useless eventually. The same often can happen with insect sprays, as roaches and other pests develop into mutant strains that are capable of surviving exposure to these pesticides. Such species, with their short cycles of birth, reproduction, and death, are extremely well equipped for survival as a group, which explains why many an unpleasant "bug" (whether a bacterium or an insect) has long been with us. (See Mutation for more on this subject.)

REAL-LIFE APPLICATIONS

"Proving" Evolution

Later in this essay, we look at examples of evolution in action and other phenomena that support the ideas of evolutionary theory. But before examining these many "proofs" of evolution, a few words should be said about the very fact that evolution seems to require so much more proof than most other scientific theories.

All scientific ideas must be capable of being proved or disproved, of course, but the demand for proof in the case of evolution goes far beyond the usual rigors of science. In fact, at this point, the people demanding proof are not scientists but certain sectors of the population as a whole—in particular, religious groups or individuals who fear evolution as a challenge to their beliefs.

QUANTUM MECHANICS: A MUCH MORE DIFFICULT IDEA. By contrast, quantum mechanics, though it encompasses ideas completely opposed to common sense, has not sustained anything approaching the same challenge or the demand for proof that evolution has encountered from nonscientists. A theory in physics and chemistry that details the characteristics of energy and matter at a subatomic level, quantum mechanics goes against such common assumptions as the idea that we

can know both the location and the speed of an object. It is as though science had proved that down was up and up was down. If there were ever a "dangerous" theory, inasmuch as it undermines all our assumptions about the world, it is quantum mechanics not evolution, which is a fairly straightforward idea by comparison.

Quantum mechanics has gone virtually unchallenged (at least on a social or moral, as opposed to a scientific, basis), whereas even today there are many people who refuse to accept the idea of evolution. Granted, quantum mechanics is a much younger idea, having originated only in the 1920s, and it is vastly more difficult to understand. But the real reason why evolution has come under so much more challenge, of course, has to do with the fact that it is perceived (mistakenly) as challenging the primacy of God.

JUST A THEORY? One of the aspects of evolution often cited by opponents is the fact that it is, after all, the *theory* of evolution. The implication is that if it is still just a theory, it must be open to question. In a sense, this is accurate: for scientific progress to continue, ideas should never be accepted as absolute, unassailable truths. But this is not what opponents of evolution are getting at when they cite its status as a "mere" theory. In fact, their use of this point as a basis for attack only serves to illustrate a misunderstanding with regard to the nature of scientific knowledge.

The word *theory* in "theory of evolution" simply means that evolutionary ideas have not been and, indeed, cannot be tested in every possible circumstance. Most ideas in science are simply theories rather than laws because in few cases is it possible to say with absolute certainty that something always will be the case. One of the few actual scientific laws is the conservation of energy, which holds that for all natural systems the total amount of energy remains the same, though transformations of energy from one form to another take place. This has been tested in such a wide variety of settings and circumstances that there is no reason to believe that would it ever *not* be the case.

By contrast, there probably never will be enough tests on evolution to advance it to the status of a law. The reason is quite simply that evolution takes a long time. Some examples, such as the instances of industrial melanism that we discuss later, unfold within a short enough period of time that humans can observe them. In general, however, evolutionary processes take place over such extraordinarily long spans of time that it would be impossible to subject them to direct observation.

None of this, however, does anything to discredit evolutionary theory. For that matter, the idea that the entire physical world is made of atoms is still technically a theory, though there is no significant movement of people attempting to discredit it. The reason, of course, is that atomic theory does not seem to contradict anyone's idea of God. (This was not always the case, however. Almost 2,500 years ago, a Greek philosopher named Democritus developed the first atomic theory, but because his ideas were associated with atheism, atomic theory was largely rejected for more than two millennia.)

FACING THE FACTS. If people really understood the word theory, they would give it a great deal more respect. Unfortunately, the word so often is misused and applied to anything that has not been proved that it has begun to seem almost like an insult to call evolution a theory. After all, in the present essay, we refer to acquired characteristics as a theory, and in everyday life one often hears much less respectable ideas given the status of theory. For this reason, it is worth taking note of the process, from observation to hypothesis to the formulation of general statements, that goes into the development of a truly scientific theory.

In forming his theory of evolution, Darwin began with several observations about the natural world. Among the things he observed is the fact, which we noted earlier, that for a particular species, more individuals are born than can possibly survive with available resources. On the basis of this observation, he formed a hypothesis, or inference. His inference was that because populations are greater than resources, the members of a population must compete for resources.

A theory is made up of many hypotheses, but to proceed from a collection of hypotheses to a true theory, these inferences must be subjected to rigorous testing. Thus, Darwin, in effect, said to himself, "Is what I have said true? *Are* there more individuals of a species than there are available resources?" Then he began looking for examples, and like a true scientist, he did so with the attitude that if he found examples that con-

tradicted his hypothesis, he would reject the hypothesis *and not the facts.*

As it turns out, of course, there are always more members of a population than there are resources. This can be illustrated in a small way by observing a litter of puppies or piglets struggling to obtain milk from their mother. Chances are that the mother will not have enough teats for all her babies, and the "runt," unless it is able to force its way through the others to the milk source, may die. Only after testing this hypothesis and other hypotheses, such as that of natural selection, did Darwin formulate his theory.

Evolution and Religion

The fact that some puppies or piglets die for lack of milk is not a nice or pleasant thought, but it is the truth. Again, like a true scientist, Darwin accepted reality, without attempting to mold it to fit his personal beliefs about how things should be.

As a great thinker from the generation that preceded Darwin's, the Scottish philosopher David Hume (1711–1776), wrote in his *Enquiry Concerning Human Understanding:* "There is no method of reasoning more common, and yet more blamable, than, in philosophical disputes, to endeavor the refutation of a hypothesis, by a pretense of its dangerous consequences to religion and morality." In other words, there is an understandable, but nonetheless inexcusable, human tendency to evaluate ideas not on the basis of whether they are true but rather on the basis of whether they fit with our ideas about the world.

A scientist may be a Christian, or an adherent of some other religion, and still approach the topic of evolution scientifically—as long as he or she does not allow religious convictions to influence acceptance or nonacceptance of facts. The scientist should start with no preconceived notions and no allegiance to anything other than the truth. If that person's religious conviction is strong enough, it can weather any new scientific idea.

Confusing atheism with science. This brings up an important point regarding the alleged conflict between religion and science. Not all the blame for this belongs with religious groups or individuals who shut their minds to scientific knowledge. Many scientists over the years likewise have adopted the fallacy of maintaining that religion and science are somehow linked, in this case using scientific facts as a basis for rejecting religion.

One such scientist was Darwin himself, who embraced agnosticism because his own findings had proved that the biblical account of creation cannot be *literally* true. In this religious choice, he was following in a family tradition: his grandfather, the physiologist Erasmus Darwin (1731–1802), belonged to the mechanist school, a muddle of atheism, bad theory, and genuine science.

The mechanists claimed that humans were mere machines whose activities could be understood purely in terms of physical and chemical processes. Claims such as these ultimately led to the discrediting of their movement, whose ideas failed to explain such biological processes as growth. At the same time, such mechanist philosophers as the French physician and philosopher Julien de La Mettrie (1709–1751) went far beyond the territory of science, teaching that atheism was the only road to happiness and that the purpose of human life was to experience pleasure.

The thinker who perhaps did the most to confuse science and atheism was one of Darwin's most significant early followers, the German natural scientist and philosopher Ernst Haeckel (1834–1919). It was Haeckel, not Darwin, who first proposed an evolutionary explanation for the origin of human beings, which, of course, was a major step beyond even Darwin's claim that all of life had evolved over millions of years.

In the course of developing this idea, Haeckel, who was a practicing Christian until he read Darwin's *On the Origin of Species by Means of Natural Selection,* renounced his faith and adopted a belief system he called monism, which is based on the idea that there is only a physical realm and no spiritual one. Technically, Haeckel was not an atheist but a pantheist, since his philosophy included the idea of a single spirit that lives in all things, both living and nonliving. Whatever the case, Haeckel's monism is no more scientific than Christianity.

Humans and "monkeys." It is interesting that the man who put forward the notorious idea that humans and apes are related also would attempt to turn evolution into a sort of "proof" of atheism. In fact, the evolutionary connection between humans and lower primates, or "monkeys," has long been the most powerful point of contention between religion and evolution.

This, in fact, remains one of the most challenging aspects of evolutionary theory—not because it is hard to see how the human body is similar to an ape's body but because there is such a vast difference between a human mind and that of an ape. Whereas our physical similarity to primates is easy to establish, the fact is that no other animal—ape, dolphin, pig, or dog—comes close to humans in terms of reasoning ability. Nor is it reasoning ability alone that separates humans from other animals. Humans possesses a propensity for conceptualization and a level of self-awareness that sets them completely apart from other creatures, so much so that the brains of apes, cats, birds, and even frogs seem more or less alike compared with that of a human.

Animals are concerned with a few things: eating, sleeping, eliminating waste, and procreating. Some mammals have the ability to engage in play, but there is still no comparison between even the most advanced mammalian brains and that of a human. Other primates have the ability to use sticks or stones as tools, but only humans—practically from the beginning of the species 2.5 million years ago—have the ability to fashion tools. Only humans are gifted, or cursed, with restless minds ever in search of new knowledge.

Does any of this disprove evolution? It does not. Does it pose a significant challenge to the idea that humans and other primates evolved from a common ancestor? Not as it has been stated here. All that has been said in the preceding paragraphs is simply a matter of everyday observation, but it is not a scientific hypothesis, let alone a theory. Clearly, there are some questions still to be answered as to why and how humans developed brains so radically different from those of other primates, but the place for such questioning is *within* the realm of science not outside it.

CREATIONISM. Another thing we can say about the human mind is that it has a tendency to mold ideas toward its own preconceptions as to how things should be. As Hume observed, there is a great temptation, in the minds of all people, to demand that scientific facts conform to a particular set of religious or political beliefs. Such is the case with creationism and "intelligent design theory," two scientific belief systems whose adherents have attempted to challenge evolutionary theory.

Creationism, which sometimes goes by the name of creation science, is based on the belief that God created the universe and did so in a very short period of time. This claim, creationists maintain, can be supported by scientific evidence. Scientific evidence, however, is not really what drives creationism, which is based on a literal reading of the first two chapters of the Book of Genesis. Taken to an extreme, this means that God created the universe about 6,000 years ago in six days of 24 hours each.

Adherents of creationism begin with the premise of a six-day Creation (or at least, a very young Earth) and then look for facts to support the premise—exactly the opposite of the approach taken by true science. The findings of creationists do not change much over the years, unlike evolutionary science, which has continued to develop with new discoveries.

Sometimes creationists attempt to use the findings of evolutionary science against it. For instance, they may interpret industrial melanism (the adaptation of moths to discoloration in the environment caused by pollution, discussed later in this essay) as proof that organisms can change very quickly. This, of course, does not take into account the fact that moths have very short life spans compared with humans, for whom evolutionary change takes much longer. Creationists also point to areas of evolutionary theory where all scientists are not in agreement, citing these as "proof" that the whole theory is unsound.

INTELLIGENT DESIGN THEORY AND THE COURT BATTLE. In contrast to creationism, intelligent design theory is not based on any particular religious position. Instead, it begins with an observation that would find a great deal of agreement among many people, including those who support evolutionary theory. The idea is that evolution alone does not explain fully how life on Earth came to exist as it does, with all its complexity and order. According to intelligent design theory, there must have been some intelligence behind the formation of the universe.

There is another contrast between intelligent design theory and creationism. Whereas it is hard to imagine a genuine scientist embracing creationism, it is not difficult at all to picture a scientific thinker adopting the viewpoint of intelligent design. In fact, this has happened, though long before the "movement" had a name.

Darwin's contemporary, the English naturalist Alfred Russel Wallace (1823–1913), who published his own theory of evolution at about the same time as Darwin's *Origin of Species,* parted ways with Darwin because he maintained that there must be a spiritual force guiding evolution. Only such a force, he maintained, could explain the human soul. From a philosophical and theological standpoint, this idea has a great deal of merit, but because it cannot be tested, it cannot truly be regarded as science.

Neither creationism nor intelligent design has received any support in the scientific community—nor, during court battles over the teaching of creationism in the public schools during the 1980s, did that idea receive the support of the United States justice system. Creationism, the courts ruled, is a religious and not a scientific doctrine. Evolutionary theory is based on an ever increasing body of evidence that is both observable and reproducible. To teach these other doctrines alongside evolution in the public schools would convey the impression that creationism and intelligent design had been subjected to the same kinds of rigorous tests that have been applied to evolution, and this is clearly not the case.

Evidence for Evolution

A great deal of evidence for evolution appeared in the seminal text of evolutionary theory (mentioned previously), *On the Origin of Species by Means of Natural Selection,* which Darwin published in 1859. In fact, he had collected much of the evidence he discusses in this volume nearly three decades earlier, from 1831 to 1836, aboard a scientific research vessel off the coast of South America. (He delayed publication because he rightly feared the controversy that would ensue and resolved to present his ideas only when he learned that Wallace had developed his own theory of evolution.)

Just 22 years old, Darwin traveled on the HMS *Beagle,* from which he collected samples of marine life. His most significant work was done on the Galápagos Islands some 563 mi. (900 km) west of Ecuador. As he studied organisms there, Darwin found that they resembled species in other parts of the world, but they were also unique and incapable of interbreeding with similar species on the mainland. He began to suspect that for any particular environment, certain traits came to the forefront, favored for survival by nature.

Back in England, he already had seen such a mechanism at work in the artificial breeding of pigeons, whereby breeders favored certain gene pools—for instance, white-tailed birds—over others. (Breeders of dogs and other animals today still employ artificial-selection techniques to produce desirable strains.) Darwin posited a similar process of selection in nature, only this one was not artificial, directed by a goal-oriented human intelligence, but natural and guided by the need for survival.

THE SPREAD OF SPECIES. Among the phenomena Darwin observed in the Galápagos was the differentiation among the 13 varieties of finch (a type of bird) on the islands as well as the contrasts among these finches and their counterparts on the mainland. As Darwin began to discover, they shared many characteristics, but each variety had its own specific traits (for instance, the ability to crack tough seeds for food) that allowed it to fill a particular niche in its own environment.

From the beginning Darwin was influenced by the recent findings in geology, a newly emerging science whose leading figures maintained that Earth was very, very old. (These scientists included the Scottish geologist Charles Lyell [1797–1875], whose *Principles of Geology,* published between 1830 and 1833, Darwin read aboard the *Beagle*) The relationship between geology and evolution has persisted, and findings in the earth sciences continue to support evolutionary theory.

Among the leading ideas in geology and other geosciences since the mid–twentieth century is plate tectonics, which indicates (among other things) that the continents of Earth are constantly moving. (See Paleontology for further discussion of this topic.) This idea of continental drift provided a mechanism for species differentiation of the kind Darwin had observed.

It appears that in the past, when the landmasses were joined, organisms spread over all available land. Later, this land moved apart, and the organisms became isolated. Eventually, different forms evolved, and in time these distinct organisms became incapable of interbreeding. This is what occurred, for instance, when the Colorado River cut open the Grand Canyon, separating groups of squirrels who lived in the high-



Vampyrum bat. Widely divergent organisms sometimes possess a common structure, adapted to their individual needs over countless generations yet reflective of a shared ancestor. The cat's paw, the dolphin's flipper, the bat's wing, and the human hand are all versions of the same original five-digit appendage, called the pendtadactyl limb. *(© Gary Braasch/Corbis. Reproduced by permission.)*

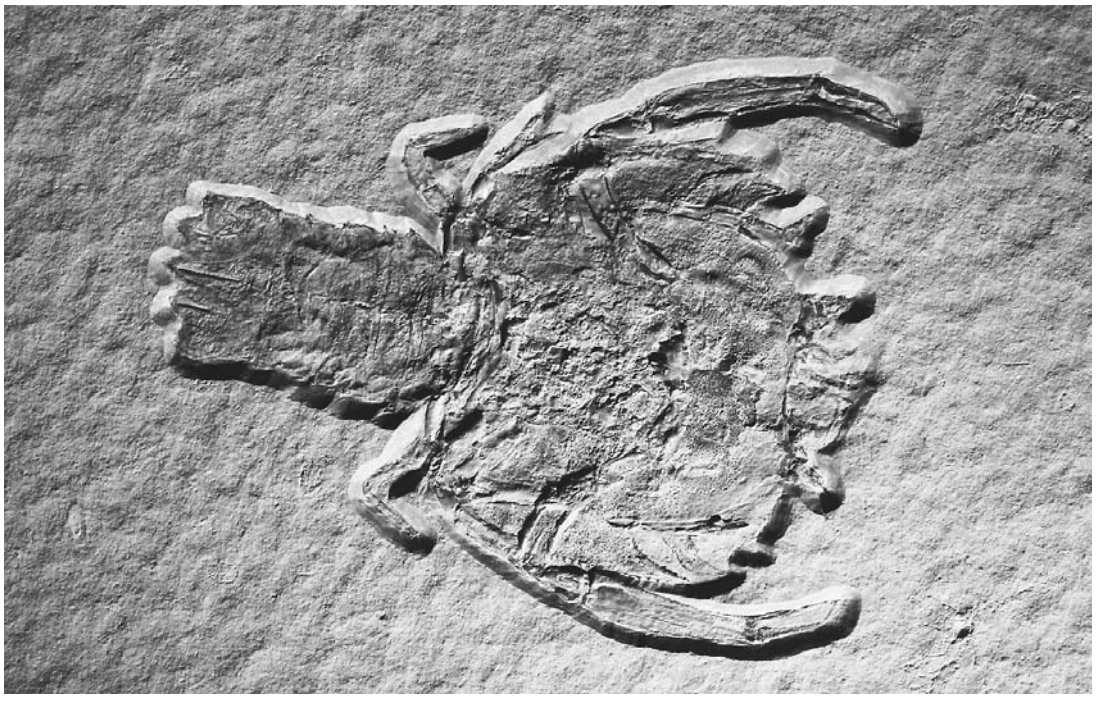
altitude pine forest. Eventually, populations ceased to interbreed, and today the Kaibab squirrel of the northern rim and the Abert squirrel of the south are separate species.

COMMON ANCESTRY. Darwin recognized that some of the best evidence for evolution lies hidden within the bodies of living creatures. If organisms have a history, he reasoned, then vestiges of that history will linger in their bodies—as studies in comparative anatomy show. An example is a phenomenon that sounds as if it is made up, but it is very real: snake hips. Though their ancestors ceased to walk on four legs many millions of years ago, snakes still possess vestigial hind limbs as well as reduced hip and thigh bones.

In some cases widely divergent organisms possess a common structure, adapted to their individual needs over countless generations yet reflective of a shared ancestor. A fascinating example of this is the pentadactyl limb, a five-digit appendage common to mammals and found, in modified form, among birds. The cat's paw, the dolphin's flipper, the bat's wing, and the human hand are all versions of the same original, an indication of a common four-footed ancestor that likewise had limbs with five digits at the end.

The embryonic forms of animals also reflect common traits and shared evolutionary forebears. This is why most mammals look remarkably similar in early stages of development. In some cases animals in fetal form will manifest vestigial features reflective of what were once functional traits of their ancestors. Thus, fetal whales, while still in their mothers' wombs, produce teeth after the manner of all vertebrates (creatures with an internal framework of bones), only to reabsorb those teeth, which they will not need in a lifetime spent filtering plankton through their jaws.

The molecular "language" of DNA also provides evidence of shared evolutionary lineage. When one studies the DNA of humans and chimpanzees, very close similarities rapidly become apparent. Likewise, there are common structures in the hemoglobin, or red blood cells, of different types of organisms. Comparisons of hemoglobin make it possible to pinpoint the date of the last common ancestor of differing species. For example, hemoglobin analysis reveals an ancestor common to humans and frogs dating



Lobster fossil from the late Jurassic period. The preserved remains of such prehistoric life-forms appear in the order of their evolution in the strata, or layers, of Earth's surface, which geologists are able to date: the age of a stratum always correlates with the fossils discovered there. *(© Layne Kennedy/Corbis. Reproduced by permission.)*

back 330 million years, whereas the common human and mouse ancestor lived 80 million years ago, and the ancestor we share with the rhesus monkey walked the earth "only" 26 million years ago.

THE FOSSIL RECORD. The fossil record also provides an amazing amount of evidence concerning common ancestors. Fossilized remains of invertebrates (animals without an internal skeleton), vertebrates, and plants appear in the strata or layers of Earth's surface in the same order that the complexities of their anatomy suggest. The more evolutionarily distant organisms lie deeper, in the older layers, beneath the remains of the more recent organisms. Geologists are able to date rock strata with reasonable accuracy, and the age of a layer always correlates with the fossils discovered there. In other words, there would never be a stratum dating back 400 million years that contained fossils of mastodons, which evolved much later.

A fossil is the remains of any prehistoric lifeform, especially those preserved in rock before the end of the last ice age, about 10,000 years ago. The process by which a once living thing becomes a fossil is known as *fossilization.* Generally, fossilization involves changes in the hard portions, including bones, teeth, and shells. This series of changes, in which minerals are replaced by different minerals, is known as *mineralization.*

Fossilized remains of single-cell organisms have been found in rock samples as old as 3.5 billion years, and animal fossils have been located in rocks that date to the latter part of Precambrian time, as long ago as one billion years. Certain fossil types, known as index fossils or indicator species, have been associated strongly with particular intervals of geologic time. An example is the ammonoid, a mollusk that proliferated for about 350 million years, from the late Devonian to the early Cretaceous periods, before experiencing mass extinction.

The fossil record is far from an open book, however, and interpreting fossil evidence requires a great deal of judgment. All manner of natural phenomena such as earthquakes can destroy fossil beds, rendering the evidence unreadable or at least unreliable. Nor is it a foregone conclusion that the animals who left behind fossils are fully representative of the species existing at a given time. Fossils are far more likely to be preserved in certain kinds of protected aquat-

ic environments, for instance, than on land (particularly at higher elevations, where erosion is a significant factor), and therefore paleontologists' knowledge of life forms in the distant past is heavily weighted toward marine creatures.

Faunal succession and other forms of dating. Key to the demonstration of evolution is the age of samples and the idea that many of the processes described took place a long, long time ago. This raises the question of how scientists know the age of things. In fact, they have at their disposal several techniques, both relative and absolute, for dating objects.

One of the earliest ideas of dating in geology was faunal dating, or the use of bones from animals (fauna) to determine age. This was the brainchild of the English engineer and geologist William Smith (1769–1839), whose work is an example of the fact that evolutionary ideas were "in the air" long before Darwin. While excavating land for a set of canals near London, Smith discovered that any given stratum contains the same types of fossils, and therefore strata in two different areas can be correlated. Smith stated this in what became known as the law of faunal succession: all samples of any given fossil species were deposited on Earth, regardless of location, at more or less the same time. As a result, if a geologist finds a stratum in one area that contains a particular fossil and another in a distant area having the same fossil, it is possible to conclude that the strata are the same.

Faunal succession is relative, meaning that it does not provide clues as to the actual age in years of a particular sample. Since the mid–twentieth century, however, scientists have had at their disposal several means for absolute dating, which make it possible to determine the rough age of samples in years. Most of these mechanisms for dating are based on the fact that over time, a particular substance converts to another, mirror substance. By comparing the ratios between them, it is possible to arrive at an estimate as to the amount of time that has elapsed since the organism died.

Chief among the techniques for absolute dating is radiometric dating, which uses ratios between two different kinds of atoms for a given element: stable and radioactive isotopes. Isotopes are atoms that differ in their number of neutrons, or neutrally charged subatomic particles, and radioactive isotopes are ones that spontaneously eject various high-energy particles over time. Because chemists know how long it takes for half the isotopes in a given sample to stabilize (a half-life), they can judge the age of such a sample by examining the ratio of stable to radioactive isotopes. In the case of uranium, one isotopic form, uranium 238, has a half-life of 4,470 million years, which is very close to the age of Earth itself.

Evolution at Work

Every creature that exists today is the result of an incredibly complex, lengthy series of changes brought about by mutation and natural selection, changes that influenced the evolution of that life-form. Take for instance the horse, whose evolutionary background is as well-documented as that of any creature.

The horse family, or Equidae, had its origins at the beginnings of the Eocene epoch about 54 million years ago. This first ancestor, known as *Hyracotherium* or *eohippus* ("dawn horse") was extremely small—only about the size of a dog. In addition, it had four hooves on its front feet and three on each rear foot, with all of its feet being padded, which is quite a contrast with the four unpadded, single-hoofed feet of the modern horse. These and other features, such as head size and shape, constitute such a marked difference from what we know about horses today that many scientists have questioned the status of eohippus as an equine ancestor. However, comparison with fossils from later, also extinct, horses shows a clear line of descent marked by an increase in body size, a decrease in the number of hooves, an elimination of foot pads, lengthening of the legs and fusion of the bones within, development of new teeth suited for eating grass, an increase in the length of the muzzle, and a growth in both the size and development of the brain.

Of course, this was not a clear-cut, neat, and steadily unfolding process, and some features appeared abruptly; still, the progression is there to be observed in the fossil record. Over the course of the many millions of years since eohippus, species have emerged that were distinguished by a particular feature—for example, teeth size and shape—only to disappear if conditions favored species with other traits. Evolutionary lines have branched off, with some dead-ending, and others continuing.

Thus, during the Miocene epoch, which lasted from about 26 million to 7 million years ago, various evolutionary branches competed for a time until the emergence of *Parahippus.* This species had teeth adapted for eating grass, in contrast to those of earlier horse ancestors, which grazed on leaves and other types of vegetation that did not require strong teeth. After Parahippus came *Merychippus,* which resembled a modern pony, and from which came numerous late-Miocene evolutionary lines. Most of these were three-toed, but *Pliohippus* had one toe per foot, and it was from this form that the genus *Equus* (which today includes horses, donkeys, and zebras) began to emerge in the late Pliocene epoch about 3 million years ago.

INDUSTRIAL MELANISM AND THE PEPPER MOTH. Despite the staggering spans of time involved in evolution, one need not look back billions of years to see evolution at work. Both natural selection and mutation play a role in industrial melanism, a phenomenon whereby the processes of evolution can be witnessed within the scale of a human lifetime. Industrial melanism is the high level of occurrence of dark, or melanic, individuals from a particular species (usually insects) within a geographic region noted for its high levels of dark-colored industrial pollution.

With so much pollution in the air, trees tend to be darkened, and thus a dark moth stands a much greater chance of surviving, because predators will be less able to see it. At the same time, there is a mutation that produces dark-colored moths, and in this particular situation, these melanic varieties are selected naturally. On the other hand, in a relatively unpolluted region, the lighter-colored individuals of the same species tend to have the advantage, and therefore natural selection does not favor the mutation.

The best-known example of industrial melanism occurred in a species known as the pepper moth, or *Biston betularia,* which usually lives on trees covered with lichen. (An example of a lichen is reindeer "moss"; see Symbiosis.) Prior to the beginnings of the Industrial Revolution in England during the late eighteenth century, the proportion of light-colored pepper moths was much higher than that of dark-colored ones, both of which were members of the same species differentiated only by appearance.

As the Industrial Revolution got into full swing during the 1800s, factory smokestacks put so much soot into the air in some parts of England that it killed the lichen on the trees, and by the 1950s, most pepper moths were dark-colored. It was at that point that Bernard Kettlewell (1907–1979), a British geneticist and entomologist (a scientist who studies insects), formed the hypothesis that the pepper moths' coloration protected them from predators, namely birds.

Kettlewell therefore reasoned that, before pollution appeared in mass quantities, light-colored moths had been the ones best equipped to protect themselves because they were camouflaged against the lichen on the trees. After the beginnings of the Industrial Revolution, however, the presence of soot on the trees meant that light-colored moths would stand out, and therefore it was best for a moth to be dark in color. This in turn meant that natural selection had favored the dark moths.

In making his hypothesis, Kettlewell predicted that he would find more dark moths than light moths in polluted areas, and more light than dark ones in places that were unpolluted by factory soot. As it turned out, dark moths outnumbered light moths two-to-one in industrialized areas, while the ratios were reversed in unpolluted regions, confirming his predictions. To further test his hypothesis, Kettlewell set up hidden cameras pointed at trees in both polluted and unpolluted areas. The resulting films showed birds preying on light moths in the polluted region, and dark moths in the unpolluted one—again, fitting Kettlewell's predictions.

ANGIOSPERMS AND GYMNOSPERMS. A final interesting example of natural selection at work lies in the comparative success rates of angiosperms and gymnosperms. An angiosperm is a type of plant that produces flowers during sexual reproduction, whereas a gymnosperm reproduces sexually through the use of seeds that are exposed, for instance in a cone. Angiosperms are a beautiful example of how a particular group of organisms can adapt to its environment and do so in a much more efficient way than that of its evolutionary forebears. On the other hand, gymnosperms, with their much less efficient form of reproduction, perhaps one day will go the way of the dinosaur.

Flowering plants evolved only about 130 million years ago, by which time Earth long since

KEY TERMS

ACQUIRED CHARACTERISTICS: Sometimes known as *acquired characters* or *Lamarckism* after one of its leading proponents, the French natural philosopher Jean Baptiste de Lamarck (1744–1829), acquired characteristics is a fallacy that should not be confused with mutation. Acquired characteristics theory maintains that changes that occur in an organism's overall anatomy (as opposed to changes in its DNA) can be passed on to offspring.

DATING: Any effort directed toward finding the age of a particular item or phenomenon. Methods of dating are either relative (that is, comparative and usually based on rock strata, or layers) or absolute. The latter, based on methods such as the study of radioactive isotopes, typically is rendered in terms of actual years or millions of years.

DNA: Deoxyribonucleic acid, a molecule in all cells and in many viruses that contains genetic codes for inheritance.

FOSSIL: The mineralized remains of any prehistoric life-form, especially those preserved in rock before the end of the last ice age.

FOSSILIZATION: The process by which a once living organism becomes a fossil. Generally, fossilization involves mineralization of the organism's hard portions, such as bones, teeth, and shells.

GENE: A unit of information about a particular heritable (capable of being inherited) trait that is passed from parent to offspring, stored in DNA molecules called *chromosomes.*

GEOLOGIC TIME: The vast stretch of time over which Earth's geologic development has occurred. This span (about 4.6 billion years) dwarfs the history of human existence, which is only about 2.5 million years. Much smaller still is the span of human civilization, only about 5,500 years.

had been dominated by another variety of seed-producing plant, the gymnosperm, of which pines and firs are an example. Yet in a relatively short period of time, geologically speaking, angiosperms have become the dominant plants in the world. In fact, about 80% of all living plant species are flowering plants. Why did this happen? It happened because angiosperms developed a means whereby they coexist more favorably than gymnosperms with the insect and animal life in their environments.

Gymnosperms produce their seeds on the surface of leaflike structures, and this makes the seeds vulnerable to physical damage and drying as the wind whips the branches back and forth. Furthermore, insects and other animals view gymnosperm seeds as a source of nutrition. In an angiosperm, by contrast, the seeds are tucked safely away inside the ovary. Furthermore, the evolution of the flower not only has added a great deal of beauty to the world but also has provided a highly successful mechanism for sexual reproduction. This sexual reproduction makes it possible for new genetic variations to develop, as genetic material from two individuals of differing ancestry come together to produce new offspring. (For more about angiosperms and gymnosperms, see Ecosystems and Ecology.)

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KEY TERMS CONTINUED

HYPOTHESIS: An unproven statement regarding an observed phenomenon.

INDUSTRIAL MELANISM: The high level of occurrence of dark, or melanic, individuals from a particular species (usually insects) within a geographic region noted for its high levels of dark-colored industrial pollution.

INVERTEBRATE: An animal without an internal skeleton.

LAW: A scientific principle that is shown always to be the case and for which no exceptions are deemed possible.

MINERALIZATION: A series of changes experienced by a once living organism during fossilization. In mineralization, minerals in the organism are replaced or augmented by different minerals or the hard portions of the organism dissolve completely.

MUTATION: Alteration in the physical structure of an organism's DNA, resulting in a genetic change that can be inherited.

NATURAL SELECTION: The process whereby some organisms thrive and others perish, depending on their degree of adaptation to a particular environment.

PALEONTOLOGY: The study of lifeforms from the distant past, primarily as revealed through the fossilized remains of plants and animals.

SCIENTIFIC METHOD: A set of principles and procedures for systematic study that includes observation; the formation of hypotheses, theories, and laws; and continual testing and reexamination.

THEORY: A general statement derived from a hypothesis that has withstood sufficient testing.

VERTEBRATE: An animal with an internal skeleton.

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PALEONTOLOGY

CONCEPT

Paleontology is the study of life-forms from the distant past, as revealed primarily through the record of fossils left on and in the earth. It is a subdiscipline of both the biological and the earth sciences, one that brings to bear the techniques of geologic study and several areas of biology, including botany and zoology. But the term *paleontology,* as used in the present context, also provides a convenient means of encompassing, in a single word, the study of the distant biological past. Such study, of course, is related intimately to the investigation of evolutionary processes and phenomena. In the present context, however, our concern is not so much with the theory and principles of evolution, discussed elsewhere in this book, but rather with a relatively short overview of biological history. This area of biological investigation calls upon such concepts as mass extinction and fossilization as well as the study of plant and animal forms that scientists know only from scientific reconstruction of the past rather than from direct experience. Chief among these life-forms are the dinosaurs, which dominated Earth for a period of more than 100 million years, ending about 65 million years ago. This span of time, impressive as it seems on the human scale, is minuscule compared with the entire history of life on Earth.

HOW IT WORKS

Paleontology Among the Sciences

Paleontology is the investigation of life-forms from the distant past, primarily through the study of fossilized plants and animals. Most people are familiar with fossils, a term that probably calls to mind an image of a flat piece of rock with a shadowy imprint of a leaf or animal on it. In fact, a fossil is the preserved remains of a once living organism that has undergone a process known as *mineralization,* in which the organic materials in hard parts of the organism (for example, teeth or bones) are replaced by minerals, which are inorganic.

The difference between the organic and the inorganic, which we discuss later, is more than a difference between the living and nonliving, or even the living and formerly living. For now, though, it will suffice to say that all living and formerly living things, as well as their parts and products, are organic. The stress on formerly living things is important, since paleontology by definition encompasses plants, animals, and microscopic life-forms that lived a long time ago. (As for just how long "a long time ago" really is, that subject, too, is discussed later in this essay.)

Among the fields related, or subordinate, to paleontology are paleozoology, which focuses on the study of prehistoric animal life; paleobotany, the study of past plant life; and paleoecology, the study of the relationships between prehistoric plants and animals and their environments. Despite the emphasis on past life-forms, however, paleontologists also avail themselves of evidence gleaned from observation of animals living today. In this approach, paleontology shows its relationship to geology, which, along with biology, is one of its two "parents."

GEOLOGY AND PALEONTOLOGY. One of the key concepts in geology is the principle of uniformitarianism, which arose from the early history of the geologic sciences. At

a time when the nascent science was embroiled in a debate over Earth's origins and the age of the planet, the Scottish geologist James Hutton (1726–1797) transcended this debate by focusing on the processes at work on Earth in the present day. (In terms of geologic time or even the evolution of species, the eighteenth century and twenty-first century might as well be a few seconds apart, so the expression *present day* applies to Hutton's time as much as to ours.) Rather than simply speculate as to how Earth had come into being, Hutton maintained that scientists could understand the processes that had formed it by studying the geologic phenomena they could see around them.

The reason this approach works is that natural laws do not change over time, nor do the processes that are at work within nature. On the other hand, particular processes may not be in operation at all times, nor can it be assumed that the rate at which the processes take place is the same. The two foregoing sentences encompass some of the observations made by the modern American paleontologist Stephen Jay Gould (1941–2002) with his formulation of the "four types of uniformity" in *Ever Since Darwin: Reflections in Natural History* (1977). It is certainly appropriate that paleontology and geology interface in this concept of uniform change, because both are concerned with piecing together the distant past from the materials available in the present.

In fact, from the standpoint of the earth sciences, paleontology belongs to a branch of geology known as historical geology, or the study of Earth's physical history. (This field of study is contrasted to the other principal branch of the discipline, physical geology, the study of the material components of Earth and of the forces that have shaped the planet.) Other subdisciplines of historical geology are stratigraphy, the study of rock layers, or strata, beneath Earth's surface; geochronology, the study of Earth's age and the dating of specific formations in terms of geologic time; and sedimentology, the study and interpretation of sediments, including sedimentary processes and formations.

BEFORE LIFE

Later in this essay, we consider just what is meant by "geologic time," the grand sweep of several billion years during which Earth evolved from a cloud of gases to its present form. It may be surprising to discover the large proportion of that time during which life existed on Earth; it is equally amazing to learn what a small portion of the biological history of the planet involved anything that modern humans would recognize as "life."



A MUSEUM REPRODUCTION OF NEANDERTHAL MAN, OR HOMO SAPIENS NEANDERTHALENSIS. THE SPAN OF TIME SINCE THE FIRST APPEARANCE OF THE GENUS HOMO (TO WHICH HUMANS, OR HOMO SAPIENS, BELONG) IS MINUSCULE: 2.5 MILLION YEARS COMPARED WITH 4.6 BILLION YEARS, OR ABOUT 0.04% OF THE PLANET'S HISTORY. *(© Bettmann/Corbis. Reproduced by permission.)*

For the moment, let us go even further back, to the very beginning—an almost inconceivably long time ago. Scientists believe that the universe began between 10 billion and 20 billion years ago, with an explosion nicknamed the "big bang," a cataclysm so powerful that it sent galaxies careening outward on a course they maintain even today. Among those galaxies moving outward from the universal point of origin was our Milky Way, which, about six billion years ago, began to develop a rotating cloud of cosmic gas somewhere between its center and its rim. That was the beginning of our solar system.

THE SUN AND EARTH. The center of the cloud, where the greatest amount of gases gathered, was naturally the densest and most

massive portion as well as the hottest. There, hydrogen—the lightest of all elements—experienced extraordinary amounts of compression owing to the density of the clouded gases around it, and underwent nuclear fusion, or the bonding of atomic nuclei.

This hot center became the Sun about five billion years ago, but there remained a vast nebula of gas surrounding it. As the fringes of this nebula began to cool, the gases condensed, forming solids around which particles began to accumulate. These were the future planets, including ours. The process of planetary formation took place over a span of about 500 million years. The planets contained various chemical elements, formed by nuclear fusion on the Sun—a fascinating aspect of life on Earth, since it means that the particles that make up the human body came from nuclear reactions on the stars.

THE EARLY ATMOSPHERE. The brand-new Earth possessed an atmosphere that consisted primarily of elemental hydrogen, nitrogen, carbon monoxide, and carbon dioxide. This "air" would have been unbreathable to all but a very small portion of the life-forms that exist on Earth today. Yet for the development of life, it was absolutely essential that no oxygen be present in Earth's atmosphere at that very early time.

The reason is that oxygen is an extremely reactive element, which is why it is involved in an array of chemical reactions (including combustion and rusting) known collectively as *oxidation-reduction reactions.* If oxygen had been present at that time, it likely would have reacted with other elements immediately, rather than permitting the formation of what eventually became organic materials.

WATER. Water appeared as the result of meteorite bombardment from space, which took place in the first half-billion years of Earth's existence. It might seem strange to learn that water, a compound essential to life on Earth, came from the void of space—where, as far as we know, there are no other life-forms. But this is not as strange as it sounds: water itself is inorganic, and even today frozen water exists on several planets in our solar system.

In any case, water eventually accumulated on Earth's surface in quantities sufficient for its condensation, with the result that clouds formed and rain fell on Earth more or less continually for many millions of years. It was then that the beginnings of life made their appearance, in the form of self-replicating molecules of carbon-based matter.

LIFE BEGINS

One famous cliché of science-fiction movies is the use of the phrase "carbon-based life-forms" to describe humans. In fact, *all* living things contain carbon, and if we ever do find life, intelligent or otherwise, on other planets, chances are extremely high that it, too, will be "carbon-based." Carbon, in fact, is almost synonymous with life, and hence the word *organic,* in its scientific meaning, refers to all substances that contain carbon. The only exceptions are the elemental carbon in diamonds or graphite, the carbonate forms that make up many of Earth's rocks, and such oxides as carbon dioxide and monoxide, all of which are considered inorganic.

It may sound as though a huge portion of carbon's possible forms already have been eliminated from the list of organic substances, but, in fact, carbon is capable of forming an almost limitless array of compounds with other elements, particularly hydrogen. A class of molecule known as hydrocarbons, which are nothing but strings of carbon and hydrogen molecules bonded together, is the basis for literally millions of organic compounds, from petroleum to polymer plastics. It may sound odd to hear plastics referred to as *organic,*but this only highlights the difference between the popular and scientific meanings of that term.

ORGANIC MATERIALS. At one time, *organic* referred only to living things, things that were once living, and materials produced by living things (for example, sap, blood, and urine). As recently as the early nineteenth century, scientists believed that organic substances contained a supernatural "life force," but in 1828 the German chemist Friedrich Wöhler (1800–1882) made an amazing discovery.

By heating a sample of ammonium cyanate, a material from a nonliving source, Wöhler converted it to urea, a waste product in the urine of mammals. As he later observed, "without benefit of a kidney, a bladder, or a dog," he had turned an inorganic substance into an organic one. It was almost as though he had created life. Actually, what he had discovered was the distinction between organic and inorganic material, which results from the way in which the carbon chains are arranged.

This explanation of the difference between organic and inorganic is pivotal to understanding how the beginnings of life first formed on Earth. It is an almost inconceivably large step from the nonliving to the living but not nearly so much of a jump from the inorganic to the organic. In fact, it appears that what happened on Earth in its distant past was that organic (but not living) substances underwent chemical reactions with inorganic ones to produce the rudiments of life. The American chemist Stanley Miller (1930–) illustrated this with an experiment that involved a mixture of hydrogen, methane (CH_4), ammonia (NH_3), and water. Subjected to a discharge of electric sparks intended to simulate lightning in Earth's early atmosphere, the mixture eventually yielded amino acids, which are among the chief components of proteins.

EARLY FORMS OF LIFE. The course that early forms of life followed during the first 800 million years of Earth's existence was a lengthy one, and if a person could have glimpsed Earth at any interval of a few million years during this time, it might have seemed as though nothing at all was happening. In fact, however, life-forms were undergoing the most profound changes imaginable.

That span of 0.8 billion years saw a transition from elemental carbon to organic compounds and from organic compounds to organelles, which are discrete components of cells, and finally to cells themselves—the building blocks of life. The processes by which this happened were exceedingly complicated, and modern scientists have little to go on in forming their suppositions as to how these transitions came about. Among many key pieces of information missing from the picture, for instance, is the matter of how and when DNA first appeared in cells. (For more on DNA, see Cells.)

The first cells to form were known as prokaryotic cells, or cells without a nucleus. (These cells, too, are discussed in the essay Cells.) Prokaryotic cells may have been little more than sacs of DNA that were capable of self-replication—much like bacteria today, which are themselves prokaryotic. These early forms of bacteria, which dominated Earth for many millions of years, were apparently anaerobic and eventually split into three branches: archaebacteria, eubacteria, and eukaryotes. Out of the last group grew all other forms of life, including fungi, plants, and animals.

GEOLOGIC TIME MARCHES ON

By about 2.5 billion years ago, bacteria had begun to undergo a form of photosynthesis, as plants do today. As a result, oxygen started to accumulate in Earth's atmosphere, and this had two interesting implications for life on Earth. One of the results of oxygen formation was that formation of "new" cells—that is, spontaneously formed cells that did not come from already living matter—ceased altogether, because they were killed off by reactions with oxygen. Second, aerobic respiration thereafter became the dominant means for releasing energy among living organisms.

The real history of life-forms on Earth—the portion of that history about which paleontologists can learn a great deal from observation of fossils and other materials—dates from the beginning of the Cambrian period, about 550 million years ago. At this point, about 88% of Earth's history already had passed, yet the remaining 12% contains virtually all the really dramatic events in the formation of life on Earth. Later in this essay, we examine a few analogies that help put these time periods into perspective as well as the concept of geologic time itself.

PHASES IN EARTH'S HISTORY. In the course of discussing these topics, it is sometimes necessary to make reference to geologic time divisions—eons, eras, periods, and epochs. These are not units of a specific length in years, like a century or a millennium; instead, they are distinct phases in Earth's history that historical geologists (including paleontologists) have pieced together from fossils and other materials. Their names usually refer to locations where fossils relevant to that phase of geologic time were found: for example, the Jurassic period, whose name became a household word after the release of the 1993 blockbuster movie *Jurassic Park,* is named after the Jura Mountains of Switzerland and France.

The historical juncture mentioned in the paragraph before last—the beginning of the Cambrian period, some 550 million years ago, was also the end of the Proterozoic eon, the third of three eons in what is known as Precambrian time. The fourth and present eon is the Proterozoic, which has included three eras: Paleozoic (about 550–240 million years ago), Mesozoic (about 240–65 million years ago), and Cenozoic (about 65 million years ago to the present).

CATACLYSMS AND CONTINENTAL DRIFT. The divisions between these phases have not been drawn arbitrarily; rather, they are based on evidence suggesting that those points in Earth's history were marked by violent, cataclysmic events. Once life had come into the picture, these cataclysms brought about death on a vast scale, which we discuss later, in the context of mass extinctions. A number of phenomena caused mass extinctions at various points; most notable among them was the impact of meteorites. Also significant was continental drift, which, as its name implies, is the movement of the continents from distant origins.

Just as evolutionary theory informs much of our modern thinking about biology, the theory of plate tectonics holds a dominant position in geology and related earth sciences. Plate tectonics involves the movement of large segments in the crust and the upper mantle of Earth, and one of the outcomes of such movement is continental drift.

Even today, the continents we know are moving slowly away from or toward one another, but that movement is so slow that it would take millions of years for any change to be perceptible. At one time, however, the continents were distributed quite differently than they are today. For example, at the end of the Permian period and the beginning of the Triassic, when the dinosaurs began to appear on the scene, all of Earth's landmasses were joined in a single continent, Pangea, that stretched between the North and South Poles and was surrounded by a vast ocean.

REAL-LIFE APPLICATIONS

Our Place in the Grand Scheme of Things

All areas of historical geology—including paleontology—are concerned with geologic time, a term that refers to the great sweep of Earth's history. This is a timescale that dwarfs the span of human existence, and to study the history of life on Earth, a mental adjustment of monumental proportions is required. One must discard all notions used in studying the history of human civilization, including such concepts as *modern, medieval,* and *ancient,* which are essentially useless when discussing geologic time.

Human civilization has existed for about 5,500 years, the blink of an eye in geologic terms. Even the span of time since the first appearance of the genus *Homo* (to which humans, or *Homo sapiens,* belong), is minuscule: 2.5 million years compared with 4.6 billion years, or about 0.04% of the planet's history. A couple of analogies, one to a shorter span of time and another to a measurement of space, will help us understand the scope of time encompassed in the evolution of species.

LIFE APPEARS IN JUNE—SO TO SPEAK. Suppose that the entire history of Earth were likened to a single year of 365.25 days, starting with the formation of the planet from a cloud of dust and ending with the present. At what point in the year would the first aerobic life-forms appear? We are not talking about anything approaching a human or even a clam or a fern or a piece of algae—just a single-cell organism that depends on oxygen for energy.

One might guess that such life-forms appeared sometime in January, or at least by the end of winter in late March. In fact, the first aerobic single-cell life-forms arose around June 15—nearly halfway through a year. Even at about the time of Thanksgiving, the most complex organisms would be fish and a few early amphibians.

We tend to associate the dinosaurs with the early phases of Earth's history, but this only illustrates our distorted view of geologic time. In fact, the Jurassic period would be analogous to a period of about five days from December 15–20. By Christmas Day, all remaining dinosaurs would have been headed toward extinction, their dead bodies eventually forming the fossil fuels that power present-day civilization.

By this point we are within a few days of the year's end, and yet nothing remotely resembling a human has appeared. Our own genus would not come on the scene until around 8:00 P.M. on December 31. The New Year's Eve countdown would be nearing by the time human civilization began, at about 42 seconds before midnight. Christ's birth would have occurred at about 14 seconds before midnight, and the final 10-second countdown would begin about the time the Roman Empire fell. The life span of the average person would correspond to approximately half a second or less.

ANOTHER ANALOGY: LOS ANGELES TO NEW YORK. To use another analogy, suppose we are driving from

Los Angeles to New York City, and that this distance corresponds to Earth's history. Once we reach western Nebraska, with about 46% of the distance behind us, we would come to the beginning of the Proterozoic era and the origins of aerobic life-forms. One might wonder why "nothing" happened on all those long miles from L.A. through the deserts, mountains, and plains of the western United States, but as we have seen, a great deal happened: Earth formed from a cloud of gas, was pounded by meteors, and gradually became the home to oceans.

The end of the Proterozoic era (about 545 million years ago) would be at about 88% of the distance from Los Angeles to New York—somewhere around Pittsburgh, Pennsylvania. By this point, the continental plates have formed, oxygen has entered the atmosphere, and soft-bodied organisms have appeared. We are a long way from Los Angeles, and yet almost the entire history of life on Earth, at least in terms of relatively complex organisms, lies ahead of us.

If we skip ahead by about 339 million years—a huge leap not only in time but also in biological development—we come to the point when the dinosaurs appeared. We are now 95% of the way from the beginning of Earth's history to the present, and if it is measured against the distance from Los Angeles to New York, we would be somewhere around Scranton, in eastern Pennsylvania. Another 89 mi. (142 km) from the Scranton area would put us at a point about 65 million years ago, or the time when the dinosaurs became extinct. We then would have less than 40 mi. (64 km) to drive to reach the period where genus *Homo* appeared, by which time we would be in the middle of Manhattan.

Compared with the distance from L.A. to New York, the span of time that *Homo sapiens* has existed would be much shorter than the drive from Central Park to the Empire State Building. The entire sweep of human civilization and history, from about a thousand years before the building of the pyramids to the beginning of the third millennium A.D., would be smaller than a city block. It is *much* smaller, in fact—close to the size of a modest storefront, or 15.54 ft. (5 m).

How Did We Get Here?

On the one hand, the history of relatively complex life-forms is relatively short compared with Earth's history; on the other hand, it is unbelievably long, when one considers the diversity of forms that have evolved in the past half-billion years. What follows is an extremely brief overview, touching on a few points in the development of life on Earth.

The discussion here is far from comprehensive, the purpose being not to provide a detailed overview of evolutionary processes but to illustrate the evolution of life-forms by a few examples. The reader is strongly encouraged to consult a textbook or other reliable information source for greater illumination of these particular topics. Along with this overview, we look at some of the more dramatic aspects of paleontologic study: dinosaurs and mass extinction.

The fossilized history of life on Earth really began in earnest only with the Cambrian period, which saw an explosion of invertebrate (without an internal skeleton) marine forms. These dominated from about 550 to about 435 million years ago. At the latter point, the boundary between the Ordovician and Silurian periods of the Paleozoic era, there occurred the first of five major mass extinctions, as the "supercontinent" of Gondwana crossed the South Pole, freezing most life-forms that were then alive. As always happened with these mass extinctions, some life-forms survived, and within a few million years life again was thriving.

COMING OUT OF THE WATER. One of the favorite subjects of modern cartoonists is the migration of creatures from the water to the land. For example, following the enactment of stiff airport security guidelines in the wake of the September 11 terrorist attacks, a *New Yorker* cartoon in late 2001 showed this evolution from fish to amphibian (a creature that can live both in the water and on the ground) and, ultimately, to the human being. Then, in the last evolutionary sequence, *Homo sapiens* is depicted in a business suit, going through an airport security scanner. Most cartoons based on this event in paleontologic history follow a common theme, which can be summed up thus: "We went through all that evolution just for *this*?"

Certainly, the transition from water to solid ground was a massive step—one of almost inconceivable importance. This invasion of the land, which probably took place about 400 million years ago, perhaps started when fishes of the Devonian period (named after Devonshire in England) began breathing oxygen near the sur-

face of shallow waters. In time they made their way onto the land, and as the number of species grew, their lobed fins developed in different ways for different groups of fish, at length becoming the many limbs and appendages specific to large groups of species, such as birds or mammals. This may seem a bit far-fetched, but even today catfish are known to pull themselves out of the water and onto land if a specific need to do so arises.

Why did the first fish leave the water? Perhaps because the water levels were receding, as they have done periodically in the course of Earth's history as a result of massive freezing of global water supplies—that is, ice ages. Whatever the reason, we can be sure of the fact that the fish were not in any way attempting to reach some "higher" state of development, nor was any force pushing them to "evolve." Therein lies one of the major misconceptions about evolution, even among many of its adherents. The very name *evolution* is somewhat unfortunate, because it suggests that life-forms are moving gradually toward a state of heightened development. Instead, they simply are adapting to circumstances that confront them; hence, the entire phenomenon might well be called by the much less dramatic-sounding name *adaptation.*

Mass Extinction

Let us now pause in our narrative to discuss examples of a phenomenon that has been mentioned several times already: mass extinction. One of the truly amazing things about the history of life on Earth is the way in which forces have seemingly conspired to wipe out virtually all living things, not just once but at least five major times, along with a number of more limited instances.

Over the course of Earth's history—even its very recent history—numerous species have become extinct, usually as a result of their inability to adapt to changes in their natural environment. In the extremely recent past (recent geologically, that is—since the end of the last ice age about 10,000 years ago), some extinctions or endangerments of species have been attributed to human activities, including hunting and the disruption of natural habitats. For the most part, however, extinction is simply a part of Earth's history, a result of the fact that organisms incapable of adaptation soon die out. This is the infamous "survival of the fittest," an aspect of evolutionary theory that many a social or political ideologue has misappropriated for the purpose of insisting that one particular ethnic or social group is naturally superior to another (see Evolution).

Why does mass extinction occur? As we noted earlier, one possible cause of mass extinction is a sudden and dramatic change in ocean levels. Other causes include volcanic eruptions or the effects of events or objects from space—the explosion of a star, perhaps, or the impact of a meteorite on Earth. Although scientists have a reasonable idea of the immediate causes of mass extinction in some cases, their understanding of the root causes still is limited. This fact was expressed by the University of Chicago paleobiologist David M. Raup, who wrote in *Extinction: Bad Genes or Bad Luck?*: "The disturbing reality is that for none of the thousands of well-documented extinctions in the geologic past do we have a solid explanation of why the extinction occurred."

THE GREAT FIVE MASS EXTINCTIONS. The five largest known mass extinctions occurred at intervals of between 50 million and 100 million years over a span of time from about 435 million to 65 million years ago. The first of them we have mentioned as perhaps being associated with the first migrations of organisms to land. This was at the end of the Ordovician period, about 435 million years ago, when a drop in the ocean level wiped out one-fourth of all marine families. No wonder some of the fish adapted to life on land!

Changes in sea level along with climate changes also appear to have brought about the second great mass extinction, which we also have mentioned, near the end of the Devonian period, about 370 million years ago. But no biological cataclysm in Earth's history can compare to the mass extinction that attended the close of the Permian period some 240 million years ago—an event so traumatic to life on Earth that it has been dubbed the *great dying.*

Imagine if 96% of all people alive today were killed—a staggering and terrifying concept. This would be far more fatalities than the combined death toll of both world wars; the Black Death of 1347–1351 and the influenza epidemic of 1918–1920; the various Nazi, Stalinist, and Maoist acts of genocide; and all major earthquakes and other natural disasters in history. Now imagine that along with all those people, 96% of all other life-forms—plants and trees, birds and fishes, single-cell organisms and the



DINOSAURS DOMINATED EARTH FOR A PERIOD OF MORE THAN 100 MILLION YEARS, ENDING ABOUT 65 MILLION YEARS AGO. THE FLYING TRICERATOPS, A CREATURE OF THE LATE CRETACEOUS PERIOD, MAY HAVE BEEN A LINK BETWEEN DINOSAURS AND BIRDS. *(© Kevin Schafer/Corbis. Reproduced by permission.)*

like, which vastly outnumber the relatively small human population of Earth—all ceased to exist as well. Such was the almost incomprehensible scale of the so-called great dying, an event whose cause has not been determined, though it may have resulted from a volcanic eruption in Siberia.

THE AGE OF THE DINOSAURS

Now that we have mentioned only three of the five great mass extinctions, it is appropriate to discuss the creatures that died in the fourth and fifth: the dinosaurs, or "terrible lizards." Though they were the most well-known creatures of the Mesozoic era, which lasted from about 240–65 million years ago, dinosaurs were far from the only notable species on Earth in that phase of geologic history. In fact, it was during the first period of the Mesozoic era, the Triassic, that a group of creatures destined to make a greater impact on Earth—mammals—first appeared. During this time, botanical life included grasses, flowering plants, and trees of both the deciduous (leaf-shedding) and coniferous (cone-bearing) varieties.

Backtracking just a bit, at the beginning of the Devonian period, about 410 million years ago, the first vertebrates (animals with an internal skeleton) made their appearance in the form of jawless fishes. Plant life on land consisted of ferns and mosses. Then came the late-Devonian mass extinction we have mentioned, which removed many of the newly evolved invertebrates, including most fishes. By the end of the Devonian, about 360 million years ago, fish had evolved jaws, and life was thriving on land. Among these life-forms were reptiles in the animal kingdom, and gymnosperms, or plants that reproduce sexually by spreading exposed seeds—a primary example from our own time being pine trees.

MONSTERS OF THE MESOZOIC. Although the existence of dinosaurs has been an established fact for as long as anyone alive can remember, we have had knowledge of them only since the mid–nineteenth century. It was then that early paleontologists began to piece together evidence from fossils, which revealed the record of a time when enormous reptiles had walked the earth. Not all of these dinosaurs were so large, however. Some were as small as chickens, while others—the sauropods, the largest terrestrial animals of all time—were the equivalent of half a dozen stories tall.

Some dinosaurs were awesomely fierce predators, while others were mild-mannered plant eaters. Dinosaurs fell into two groups based on the

shape of their hips, which were either lizardlike or birdlike. Though the lizardlike Saurischia emerged first, they lived alongside the birdlike Ornithischia throughout the late Triassic, Jurassic, and Cretaceous periods. Ornithischia were all herbivores, or plant eaters, whereas Saurischia included both herbivores and carnivores, or meat eaters. Naturally, the most fierce of the dinosaurs were carnivores, a group that included the largest carnivore ever to walk the Earth, *Tyrannosaurus rex.*

Most dinosaurs had long tails and necks and walked on four legs, though some were bipedal, meaning either that they had only two legs or that they used only their two rear legs for movement or locomotion. Again, the shape of the creature correlated to some degree with its habits: all four-legged dinosaurs were relatively gentle, slow-moving herbivores, whereas most of the bipedal ones were fast-moving predators. Their teeth also reflected their diet: not surprisingly, carnivores had much sharper cutting surfaces shaped like serrated knives, which made it easy to rip their prey into smaller pieces before swallowing the pieces whole.

As recently as the 1970s, scientists tended to believe that dinosaurs were cold-blooded creatures markedly lacking in brain power. This view is reflected in a number of popular-culture sources, such as the 1983 song by the Police, "Walking in Your Footsteps," which suggests that if humans were to destroy themselves by nuclear warfare, they would seem even more "dumb" than the dinosaurs. By contrast, the film *Jurassic Park,* made a decade later, reflects changes in paleontologists' attitudes toward dinosaurs, gained as a result of continued research. As it turns out, dinosaurs were far from dumb, and they may even have been warm-blooded—unlike most reptiles but like birds, to whom they may have been related.

SOME TYPES OF DINOSAUR. Few creatures have ever captured the imagination of humans as much as *Tyrannosaurus rex*—a particularly impressive feat, given the fact that the last *T. rex* died tens of millions of years before humans ever came on the scene. With a name that means "absolute ruler lizard" in Greek, this terrifying creature reached a maximum length of 45 ft. (14 m) and may have weighed as much as 9 tons (8 metric tons).

T. rex must have made a truly awesome sight running through the forests of its Mesozoic world. Moving on its powerful hind legs with a gait that was at once swift and lumbering, it used its tail as a counterbalance and stabilizer. Once it had come abreast of its prey, *T. rex* probably attacked its victim with powerful head butts and then tore the animal apart with its massive jaws before ripping into it with some 60 dagger-shaped teeth as much as 6 in. (15 cm) long.

Of course, *T. rex* is notable precisely because it was so unusual among dinosaurs in size and, for the most part, power. *Deinonychus,* for example, was much smaller—only about 10 ft. (3 m) and 220 lb. (100 kg)—but these "running lizards" were still fearsome predators, noted for their sickle-like claws. The phrase "sickle-like claws" might call to mind another creature, this one made famous by *Jurassic Park: Velociraptor,* or "swift plunderer," a walking death machine that for all the terror it inspired in moviegoers (and, no doubt, in many a Mesozoic creature) attained a length of only about 6 ft. (2 m).

Among the many lessons about dinosaurs to be learned from *Jurassic Park* was the striking contrast between herbivores and carnivores, a fact emphasized by the scene in which the two children take refuge with a herd of sauropods. These gentle giants possessed four legs the size of large pillars and had extraordinarily long necks and tails. Most famous among the sauropods was the *Apatosaurus,* which achieved a length of 65 ft. (20 m) and a weight of 30 tons (27 metric tons). *Apatosaurus*'s appearance in the scene with the children was not the great creature's first time in the limelight of popular culture: known as *Brontosaurus* until the early 1990s, this dinosaur was a popular fixture of the *Flintstones* cartoon.

In addition to land-based dinosaurs, there were such creatures as the flying *Triceratops,* which may have been a link between dinosaurs and birds. (The name *raptor,* incidentally, usually refers not to a type of dinosaur, but to a bird of prey.) It should be noted that *Triceratops* and *Velociraptor* were creatures of the late Cretaceous period, during which about a hundred different dinosaur genera (plural of *genus*) flourished. This is an important point, because many books picture all manner of dinosaurs coexisting, when, in fact, various ones existed at different times over a period of about 180 million years. Also, it is worth noting that the major nonhuman "star" of *Jurassic Park* did not even live during the Jurassic period!

LATER MASS EXTINCTIONS—AND NEW LIFE

Today, of course, the dinosaurs are long gone—so distant in time, in fact, that the remains of many millions have become petroleum. This has happened in situations where specific conditions prevail: for example, the remains could not be allowed to rot, and decay had to be anaerobic and had to take place within certain types of rock. Yet oil reserves (for as long as they last) are not the only reason why the dinosaurs' disappearance was beneficial from the human standpoint. At the time when dinosaurs controlled the world, mammals were small and hid from predators such as *T. rex*. Without the mass extinction of the dinosaurs, this class of creatures might never have come to the forefront, and human beings might not have evolved.

Actually, two mass extinctions rocked the world of the dinosaurs. The first (fourth among the list of five major mass extinctions) happened at the end of the Triassic, the first period of the Mesozoic era. This was about 205 million years ago, when an asteroid may have hit Earth. Whatever the cause, the result was that creatures in the seas suffered major mass extinction. So, too, did those on the land, but many species of dinosaurs and mammals managed to survive the event, which marked the transition between the Triassic and Jurassic periods.

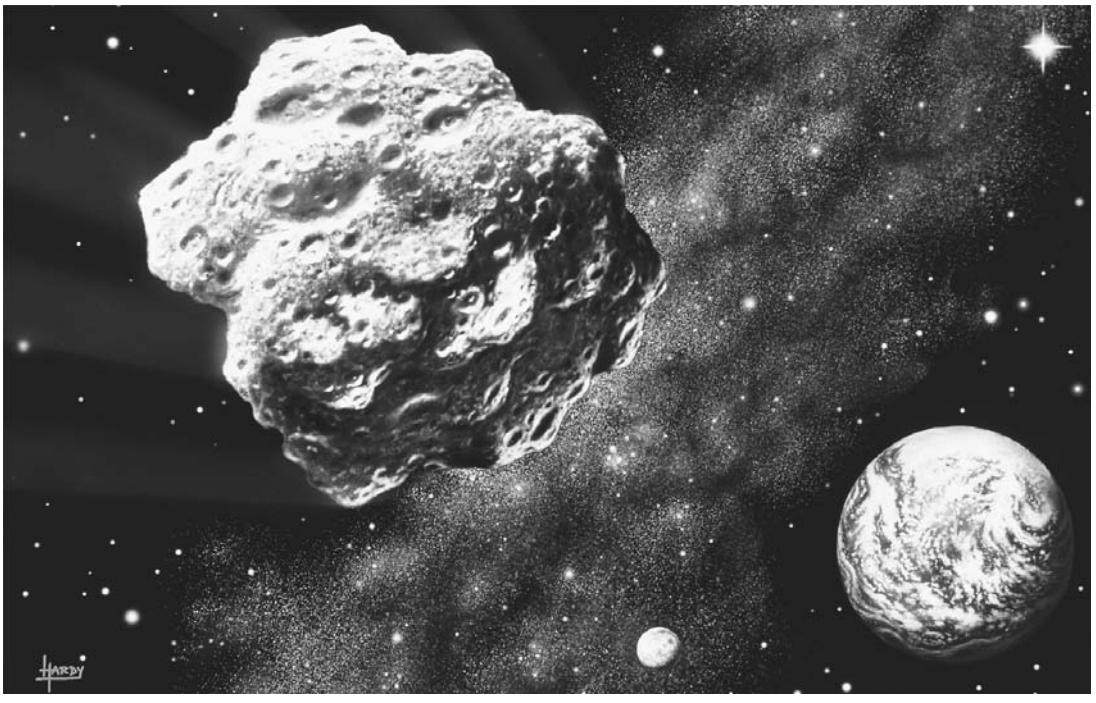
THEORIES REGARDING THE DINOSAURS' DEMISE. The dinosaurs continued to flourish for another 140 million years, and their descendants might still be walking the earth were it not for the last great mass extinction, which took place about 65 million years ago. What killed the dinosaurs? Paleontologists and other scientists have proposed several theories: a rapid climate change; the emergence of new poisonous botanical species, eaten by herbivorous dinosaurs, that resulted in the passing of toxins along the food web; an inability to compete successfully with the rapidly evolving mammals; and even an epidemic disease to which the dinosaurs possessed no immunity.

Interesting as many of these theories are, none has gained anything like the widespread acceptance achieved by another scenario. According to this highly credible theory, an asteroid hit Earth, hurtling vast quantities of debris into the atmosphere, blocking out the sunlight, and greatly lowering Earth's surface temperature. Around the world, geologists have found traces of iridium deposited at a layer equivalent to the boundary between the Cretaceous and Tertiary periods, the Tertiary being the beginning of the present Cenozoic era. This is significant, because iridium seldom appears on Earth's surface—but it *is* found in asteroids.

THE ASTEROID HITS. It appears that the asteroid smashed into what is now the northern tip of Mexico's Yucatán peninsula. Today that area is home to a crater some 6 mi. (9.6 km) deep and 186 mi. (300 km) in diameter. Note, however, that 65 million years ago, the Yucatán was not exactly where it is now. It had begun to drift in the direction of its present location, but the map of the future continent of North America was quite different from what it is today and included large submerged areas. Among them was the region of impact, which only later rose to the surface as a result of tectonic activity.

The nearest large landmass at the time was a good distance away—equivalent to northern Louisiana. But it hardly mattered that there were no dinosaurs at the point of impact. Traveling at more than 100,000 MPH (160,000 km/h), which is almost four times as fast as the fastest spacecraft built by human beings, the asteroid probably brought about an explosion as intense as many thousands of hydrogen bombs. It may not have raised a mushroom cloud per se, but it probably produced an even more dramatic formation as it sent more than 48,800 cu. mi. (200,000 km^3) of debris and gases into the atmosphere. This would be enough dust to cover the state of Mississippi to a depth of 1 mi. (1.6 km)

The sound of the impact must have been ear-shattering, even far away on what would one day become North America. Then came the tidal waves, some as tall as 394 ft. (120 m), with earthquakes soon to follow. But while these tidal waves undoubtedly caused massive localized death, or mass mortality, what really brought about the mass extinction of the dinosaurs was the aftermath of impact. All that dust in the atmosphere effectively blocked out the Sun's light, bringing about a dramatic cooling on Earth's surface. As a result, plants died, thus depriving herbivorous dinosaurs of an energy source. The herbivores died and then, in a domino effect brought about by the interdependence of components in the food web, the carnivores soon followed.



Asteroid approaching Earth. According to one theory, the mass extinction of the dinosaurs resulted from the impact of an asteroid hitting Earth, hurtling vast quantities of debris into the atmosphere, blocking out the sunlight, and greatly lowering Earth's surface temperature. *(© D. Hardy. Photo Researchers. Reproduced by permission.)*

Mammals, humans, and mass extinction. When that asteroid hit, it brought an end to the dinosaurs and their Mesozoic world, ushering in the Cenozoic era, which saw the rise of mammals. Some examples of the creatures that proliferated in the course of the past 65 million years are tiny prehistoric horses with four toes as well as a giant rhinoceros-like herbivore, both of which lived in the Eocene epoch about 40 million years ago.

As time went on, the range of species—not only animals and plants but also the much less complex organisms of the other three kingdoms (Protista, including protozoa and algae; Monera such as bacteria; and Fungi)—grew larger and larger. An ice age struck the planet about 1.65 million years ago, bringing about much smaller cases of mass extinction than the ones we have discussed. But other instances of mass extinction would occur at the hands of a creature that appeared about 2.5 million years ago: *Homo sapiens.* The ice age—which was only one of many and thus is referred to often as the "last ice age"—would prove a major turning point in the history of the human species. At the beginning, we were just embarking on the beginnings of the Stone Age, whereas at the end, just 10,000 years ago (or a few seconds ago, in geologic terms), we emerged from the cold, ready to take over the world.

Near the end of the last ice age, peoples from Siberia crossed a land bridge spanning what is today the Bering Strait between Russia and Alaska. Their descendants, of course, are the Native Americans, and *native* is a fitting term, since they arrived in the Americas about 12,000 years ago, or about 7,000 years before the Europeans' ancestors arrived in Europe. What they found, as they poured into the Americas, was a range of species quite different from those known today. There were mammoth and mastodons; giant bears, beaver, and bison; and even saber-toothed "tigers" (which were not directly related to modern-day tigers), camels, and lions. Prehistoric America was also home to horses, but these creatures and many others were wiped out by hunting. Horses did not reappear in the New World until Europeans brought them after A.D. 1500, when they would prove an indispensable aid in European efforts to conquer the Native Americans' lands.

Where to Learn More

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KEY TERMS

AEROBIC: Oxygen-breathing.

AMPHIBIAN: A creature capable of living either in the water or on solid ground.

ANAEROBIC: Non-oxygen-breathing.

CARNIVORE: A meat-eating organism.

EON: The longest phase of geologic time. Earth's history has consisted of four eons, the Hadean, Archaean, Proterozoic, and Phanerozoic. The next-smallest subdivision of geologic time is the era.

EPOCH: The fourth-longest phase of geologic time, shorter than an era. The current epoch is the Holocene, which began about 10,000 years ago.

ERA: The second-longest phase of geologic time, after an eon. The current eon, the Phanerozoic, has had three eras, the Paleozoic, Mesozoic, and Cenozoic, which is the current era. The next-smallest subdivision of geologic time is the period.

EUKARYOTE: A cell that has a nucleus and organelles (sections of the cell that perform specific functions) bound by membranes.

FOOD CHAIN: A series of singular organisms in which each plant or animal depends on the organism that precedes it. Food chains rarely exist in nature; therefore, scientists prefer the term *food web.*

FOOD WEB: A term describing the interaction of plants, herbivores, carnivores, omnivores, decomposers, and detritivores in an ecosystem. Each of these organisms consumes nutrients and passes them along to other organisms (or, in the case of the decomposer food web, to the soil and environment). The food web may be thought of as a bundle or network of food chains, but since the latter rarely exist separately, scientists prefer the concept of a food web to that of a food chain.

FOSSIL: The mineralized remains of any prehistoric life-form, especially those preserved in rock before the end of the last ice age.

FOSSILIZATION: The process by which a once living organism becomes a fossil. Generally, fossilization involves mineralization of the organism's hard portions, such as bones, teeth, and shells.

GEOLOGIC TIME: The vast stretch of time over which Earth's geologic development has occurred. This span (about 4.6 billion years) dwarfs the history of human existence, which is only about 2.5 million years. Much smaller still is the span of human civilization, only about 5,500 years.

GYMNOSPERM: A type of plant that reproduces sexually through the use of seeds that are exposed, not hidden in an ovary as with an angiosperm.

HERBIVORE: A plant-eating organism.

ICE AGE: A period of massive and widespread glaciation (the spread of glaciers). Ice ages usually occur in series over stretches of several million or even several hundred million years and have taken place periodically—often in conjunction with mass extinctions—throughout Earth's history.

INVERTEBRATE: An animal without an internal skeleton.

MASS EXTINCTION: A phenomenon in which numerous species cease to exist at

KEY TERMS CONTINUED

or about the same time, usually as the result of a natural calamity.

MINERAL: A naturally occurring, typically inorganic substance with a specific chemical composition and a crystalline structure (that is, a structure in which the constituent parts have a simple and definite geometric arrangement that is repeated in all directions).

MINERALIZATION: A series of changes experienced by a once living organism during fossilization. In mineralization, minerals in the organism are replaced or augmented by different minerals, or the hard portions of the organism dissolve completely.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals) and oxides, such as carbon dioxide.

PALEOBOTANY: An area of paleontology involving the study of past plant life.

PALEOECOLOGY: An area of paleontology devoted to studying the relationships between prehistoric plants and animals and their environments.

PALEONTOLOGY: The study of lifeforms from the distant past, primarily as revealed through the fossilized remains of plants and animals.

PALEOZOOLOGY: An area of paleontology devoted to the study of prehistoric animal life.

PERIOD: The third-longest phase of geologic time, after an era. The current eon, the Phanerozoic, has had 11 periods, and the current era, the Cenozoic, has consisted of three periods, of which the most recent is the Quaternary. The next-smallest subdivision of geologic time is the epoch.

PHOTOSYNTHESIS: The biological conversion of light energy (that is, electromagnetic energy) from the Sun to chemical energy in plants.

PROKARYOTE: A cell without a nucleus or organelles bound by membranes.

VERTEBRATE: An animal with an internal skeleton.

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BIODIVERSITY AND TAXONOMY

TAXONOMY

SPECIES

SPECIATION

TAXONOMY

CONCEPT

Taxonomy is the area of the biological sciences devoted to the identification, naming, and classification of living things according to apparent common characteristics. It is far from a simple subject, particularly owing to many disputes over the rules for classifying plants and animals. In terms of real-life application, taxonomy, on the one hand, is related to the entire world of life on Earth, but on the other hand, it might seem an ivory-tower discipline that it has nothing to do with the lives of ordinary people. Nonetheless, to understand the very science of life, which is biology, it is essential to understand taxonomy. Each discipline has its own form of taxonomy: people cannot really grasp politics, for instance, without knowing such basics of political classification as the difference between a dictatorship and a democracy or a representative government and one with an absolute ruler. In the biological sciences, before one can begin to appreciate the many varieties of organisms on Earth, it is essential to comprehend the fundamental ideas about how those organisms are related—or, in areas of dispute, *may be* related—to one another.

HOW IT WORKS

Taxonomy in Context

The term taxonomy is actually just one of several related words describing various aspects of classification in the biological sciences. In keeping with the spirit of order and intellectual tidiness that governs all efforts to classify, let us start with the most general concept, which happens to be classification itself. Classification is a very broad term, with applications far beyond the biological sciences, that simply refers to the act of systematically arranging ideas or objects into categories according to specific criteria.

While its meaning is narrower than that of classification, even taxonomy still has broader applications than the way in which it is used in the biological sciences. In a general sense, taxonomy refers to the study of classification or to methods of classification—for example, "political taxonomy," as we used it in the introduction to this essay. Literary critics sometimes refer to a writer's taxonomy of characters. Within the biological sciences, however, the term designates specifically a subdiscipline involving the process and study of the identification, naming, and classification of organisms according to apparent common characteristics.

PHYLOGENY AND NOMENCLATURE. Two other terms that one is likely to run across in the study of taxonomy are phylogeny and nomenclature. Phylogeny is the evolutionary history of organisms, particularly as that history refers to the relationships between life-forms and the broad lines of descent that unite them. Taxonomy is less fundamental a concept than phylogeny. Whereas taxonomy is a human effort to give order to all the data, phylogeny is the true evolutionary relationship between living organisms. Some scientists call phylogeny the *tree of life,* meaning that it represents the underlying hierarchical structure by which life-forms evolved and are related to one another.

The word naming was used earlier in the definition of taxonomy because it is a familiar, easily understandable word. However, a more accurate term, and one that helps illuminate the distinction between taxonomy and systematics, is



The Greek philosopher Aristotle is regarded as the father of taxonomy. The Aristotelian principles of classification were governed by the idea that there are constant, unchanging "essences" that unite classes of organisms, which is completely at odds with the empirical mentality that governs taxonomy today. *(The Library of Congress.)*

nomenclature. The latter can be defined as the act or process of naming as a well as a system of names, particularly one used in a specific science or discipline.

Homologous and Analogous Features

Before going on to discuss methods of classification, it is important to note just which characteristics of an organism's morphological aspect (i.e., structure or form) are important to scientists working in the field of taxonomy. In theorizing relationships between species, taxonomists are not interested in what are known as analogous features, those characteristics that are superficially similar but not as a result of any common evolutionary origin. Rather, they are interested in homologous features, or features that have a common evolutionary origin, even though they may differ in terms of morphological form.

One example of a shared evolutionary characteristic, discussed briefly in the essay Evolution, is the pentadactyl limb, a five-digit appendage common to mammals and found, in modified form, among birds. This is a homologous feature, indicating a common ancestor that likewise had limbs with five digits at the end. By contrast, there is no indication of a close evolutionary relationship in the fact that birds, butterflies, and bats all have wings that are similar in shape. Rather, the laws of physics require that a wing be of a certain shape in order to hold an object aloft, which is why the contour of an airplane wing, when viewed from the side, is remarkably like that of a bird's wing where it joins the animal's body.

Cladistics and Numerical Taxonomy

Cladistics is a system of taxonomy that distinguishes taxonomic groups or entities on the basis of shared derived characteristics, hypothesizing evolutionary relationships to arrange them in a treelike, branching hierarchy. The expression *derived characteristics* in this definition means that the characteristics that unite two types of organism are not necessarily present in a shared evolutionary ancestor. Rather, they have developed over the course of evolutionary history since the time of that shared ancestor.

In explaining cladistics to the ordinary human being, the vast majority of science writers seem to be at a loss as to how to make the topic comprehensible. Thus, such terms as *derived characteristics* and its opposite, *primitive characteristics,* usually are left undefined. A welcome exception is Paul Willis, who, in an on-line article for the Australian Broadcasting Corporation (see Where to Learn More) gave a wonderful illustration that was an attempt to analyze the relationships between a mouse, a lizard, and a fish.

"They've all got backbones," Willis wrote, "so the feature 'backbone' is useless [as an indication of evolutionary branching]; it's a 'primitive' character that tells you nothing. But the [derived] feature 'four legs' is useful because it's an evolutionary novelty shared only between the lizard and the mouse. This implies that the lizard and mouse are more closely related to each other than either is to the fish. Put another way, the lizard and the mouse share a common ancestor that had four legs." Willis went on to note that "the more evolutionary novelties we can find that support a particular relationship, the greater our confidence that the relationship is correct. 'Air breathing,' 'neck' and 'amniotic egg' are another three evolutionary novelties that tie the lizard

and the mouse together and leave the fish as a more distant relative."

NUMERICAL TAXONOMY. Cladistics, the most widely applied approach to taxonomy, has undergone considerable change since it was introduced by the German zoologist Willi Hennig (1913–1976) in the 1950s. Particularly important has been the marriage of cladistics with another taxonomic idea born in the mid–twentieth century, phenetics, or numerical taxonomy. Introduced by the Austrian biologist Robert Reuven Sokal (1926–) and the English microbiologist Peter Henry Andrews Sneath (1923–), numerical taxonomy is an approach in which specific morphological characteristics of an organism are measured and assigned numerical value, so that similarities between taxa (taxonomic groups or entities) can be compared mathematically. These mathematical comparisons are performed through the use of algorithms, or specific step-by-step mathematical procedures for computing the answer to a particular problem. The aim of numerical taxonomy is to remove all subjectivity (such as the taxonomist's "intuition") from the process of classification. Initially, many traditional taxonomists rejected numerical taxonomy, because its results sometimes contradicted their own decades-long studies of comparative morphological features. Nearly all modern taxonomists apply numerical methods in taxonomy, although there is often heated debate as to which particular algorithms should be used.

Identification, Classification, and Nomenclature

Earlier, taxonomy was defined in terms of its relationship to the identification, classification, and nomenclature of taxa. Let us now briefly consider each in turn, with the understanding that they are exceedingly complex, technical subjects that can be treated here in the most cursory fashion. The process of identification is a particularly complex one. When an apparently new taxon is discovered, a taxonomist prepares an organized written description of the characteristics of similar species, which are referred to as a taxonomic key. Instead of using pictures, which often poorly convey the natural variations in morphological features, taxonomists prefer to use a taxonomic key in written form, which provides much more detail and exactitude.

To put it in colloquial terms, by referring to a taxonomic key, a taxonomist may determine that if an organism "looks like a duck and quacks like a duck, it must be a duck"—only, in this instance, the taxa being compared are much more specific than the common term *duck* and the characteristics much more precisely described. (For one thing, there are several dozen species in the genus *Anas,* which includes all "proper" ducks, and many more species in the family Anatidae, or waterfowl, that are commonly called by "duck names"—including such amusingly named species as the ruddy duck, lack duck, freckled duck, and comb duck.) If there is no already established "duck" that the species in question resembles, the taxonomist may have discovered an entirely new genus, family, order, class, or even phylum.

A taxonomist may use what is called a dichotomous key, which presents series of alternatives much like a flow chart. For example, if the flowers of a sample in question are white and the stem is woody, then (depending on additional alternatives) it could be either species *A* or species *B.* If the flowers are not white and the stem is herbaceous (non-woody), then, presented with another set of additional alternatives, it is possible that the plant is either species *C* or species *D.*

CLASSIFICATION. In discussing cladistics and phenetics, we touched briefly on the *process* of classification. Suffice it to say that this process is far more complex and technically elaborate than these few paragraphs can begin to suggest. We return later to specifics of classification as they relate to systems and innovations introduced by the Greek philosopher Aristotle (384–322 B.C.), the Swedish botanist Carolus Linnaeus (1707–1778), and the English naturalist Charles Darwin (1809–1882), the three most important men in the history of taxonomy before the twentieth century. For the present, our focus is on the overall ranking system.

There are many possible ranks of classification but only seven that are part of what is known as the obligatory taxonomy, or obligatory hierarchy. These ranks are kingdom, phylum, class, order, family, genus, and species. Listed here are all possible ranks, with obligatory ranks in italics.

- *Kingdom*
- Subkingdom

- *Phylum*
- Subphylum
- Superclass
- *Class*
- Subclass
- Infraclass
- Cohort
- Superorder
- *Order*
- Suborder
- Superfamily
- *Family*
- Subfamily
- Tribe
- *Genus*
- Subgenus
- *Species*
- Subspecies

The reader occasionally may come across nonobligatory ranks, most notably subphylum, but for the most part the only ranks referred to in this book are the obligatory ones.

NOMENCLATURE. In accordance with a tradition established by Linnaeus, all group names are in Latin, thus facilitating ease of communication. There are some rules concerning names of groups: for instance, those of families use the suffix *-idae.* In the world of taxonomy, however, few rules are accepted universally. Even as basic a term as *phylum* is not universal, since botanists prefer the word *division.*

The proper name of any ranking more general than species is capitalized (e.g., phylum Chordata), with species and subspecies names in lowercase. Genus, species, and subspecies names are rendered in italics (e.g., *Homo sapiens,* or "man the wise"), while proper names of the more general groupings are presented in ordinary type (e.g., class Mammalia). If the same name appears a second time in the same article, the genus name usually is abbreviated: thus, *H. sapiens.*

Just as most people (with such rare exceptions as Cher and Madonna) are identified by two names, a personal and a family name, taxonomy makes use of a system called binomial nomenclature, in which each type of plant or animal is given a two-word name, with the first name identifying the genus and the second the species. In binomial nomenclature, the genus name is analogous to the family name, inasmuch as there are many species within a genus, and the species name is like a personal name. The difference is that whereas there may be thousands of boys and men named John Smith, there is only one species called *Homo sapiens.* Beyond the species name, there may be subspecies names: humans are subspecies *sapiens,* so our full species name with subspecies is *Homo sapiens sapiens.* Additional rules govern the inclusion of a name or an abbreviation, at the end of the species or subspecies name, to recognize the individual who first identified it.

REAL-LIFE APPLICATIONS

The Urge to Classify

One might ask what all the fuss is about. Why is classification so important? We attempt to answer that question from a few angles, including a brief look at the lengthy historical quest to develop a workable taxonomic system. But what was the original impulse that motivated that quest? One clue can be found in the Greek roots of the word *taxonomy: taxis,* or "arrangement," and *nomos,* or "law." The search for a taxonomic system represents humankind's desire to make order out of the complexities with which nature presents us. When it comes to the organization of ideas (including ideas about the varieties of life-forms), this desire for order is more than a mere preference. It is a necessity.

THE ANALOGY TO A LIBRARY. Imagine a library without any organizational system, with books simply crammed willy-nilly on the shelves. Such a place would be totally chaotic, and if one happened to find a book one was looking for, it would be a case of pure luck. The odds would be weighted heavily against such luck, especially in a university library or a large municipal or regional one. Just as a good-size university library has upward of a million volumes, and many large university libraries have several million, so there are at least a couple of million identified species, and the total may be much larger. Some entomologists (scientists who study insects) speculate that there may be ten million species of insect alone.

THE LURE OF A NEW SPECIES. When a zoologist or botanist discovers what he or she believes to be a new species, the taxonomic system provides a standard against which to check

it—rather as you would do if you thought you had discovered a book that was not in the library. If the "new" species matches an established one, that may be the end of the story—unless the scientist has discovered a new aspect of the species or a new subspecies. And if there is no match in the taxonomic "library," the scientist has discovered an entirely new life-form, with all the grand and terrifying ramifications that may ensue.

The new species might be an herb from which a cure can be synthesized for a devastating disease, or it could be a parasite that carries a new and previously unknown malady. Whatever it is, it is better to know about it than not to know, and though the vast majority of "new" species are not nearly as exciting as the preceding paragraph would imply, each has its part to play in the overall balance of life. Discovery of new species is particularly important when those species are endangered or might be in the process of disappearing even as they are identified.

Nonscientific Taxonomy

Without knowing anything about scientific taxonomy, almost anyone can begin to classify animals and perhaps plants. If we limit the discussion purely to animals, there are many basic parameters according to which we could classify them, just off the tops of our heads, as it were. For example, there are aquatic and terrestrial animals, and these general groupings can be broken down further according to biome or habitat (see Biomes). There are animals that walk, fly, swim, slither, or move by some other means. Animals can be divided according to their forms of reproduction, whether asexual or sexual, oviparous or viviparous (expelling or retaining a fertilized egg, respectively), and so on. As discussed in Food Webs, animals may be classified as herbivores, carnivores, omnivores, or detritivores or as primary, secondary, or tertiary consumers. They may be endothermic or ectothermic (warm-blooded or cold-blooded), and they may be covered with scales, feathers, fur, or skin. (In the last case, that skin may be protected by either mucus or hair.)

On and on go the categories, and if one is inclined toward a classifying mind, this kind of mental exercise can be fun. Certainly, little children enjoy it, and many educational programs and games call on the child to group animals thus. Although these kinds of groupings, and the efforts to place animals into one group or another, constitute a form of classification, there is a great difference between this and scientific taxonomy.

SCIENCE VERSUS "COMMON SENSE." Taxonomy is tied closely to evolutionary study, and Darwin's theory of evolution was a turning point in the history of scientific classification. Thus, taxonomists are concerned more with the evolutionary patterns that link organisms than they are with what may be only superficial similarities. Habitat, for instance, is significant in studying biomes, but it seldom plays a role in taxonomy. Nor is the ability to fly, as we have noted, necessarily an indicator of taxonomic similarities.

A striking example of the difference between scientific taxonomy and "common sense" classification is the fact that whales and dolphins are grouped along with other mammals (class Mammalia) rather than with fish and other creatures that most readily come to mind when thinking of aquatic organisms. In fact, whales and dolphins share not only a wide array of primitive characteristics with mammals (for example, the pentadactyl limb described earlier) but also the derived characteristic that defines *mammal*: the secreting of milk from mammary glands, by which a mother feeds her young. Not only is it impossible to get milk from a fish (even family Chanidae, known by the common name "milkfish"), but fish lack even that primitive characteristic, the pentadactyl limb, that links mammals, at least distantly, with nonmammalian creatures, such as birds (class Aves).

COMMON TERMS AND FOLK TAXONOMY. For the sake of convenience, in many places throughout this book, common terms such as *bird, horse, fish,* and so forth are used. But common terms are far from adequate in a scientific context, because such terminology can be deceptive, as exemplified by the nonduck "ducks" mentioned earlier. Likewise, shellfish and starfish are not "fish" as that term is usually understood. But while common terminology can be misleading, sometimes correlations with scientific taxonomy can be found in what is known as folk taxonomy. The latter is a term for the taxonomic systems applied in relatively isolated non-Western societies. For example, the folk taxonomy of native peoples in New Guinea identified 136 bird species in the mountains of that island, a figure that came amazingly close to the 137 species identified by the German-born



Illustration of a sea monster from "De natura rerum" by Albertus Magnus. During the Middle Ages, taxonomic writings consisted primarily of books of imaginary creatures; the first signs of scientific reawakening in taxonomy came with plant and animal catalogues by such medieval scholars as Magnus. *(© Gianni Dagli Orti/Corbis. Reproduced by permission.)*

American evolutionary biologist Ernst Mayr (1904–) when he studied New Guinea's birds using scientific methods.

Aristotle, Linnaeus, Darwin, and Beyond

Among his many other accomplishments as a thinker, Aristotle is regarded as the father of the biological sciences and of taxonomy. Among the dominant ideas in his work as a philosopher are the concepts of hierarchy and classification, and thus he took readily to the idea of classifying things. At his school in Athens, he put his students to work on all sorts of taxonomic pursuits, from listing the champions at the Pythian Games (a festival like the Olympics) to classifying the constitutions of various Greek city-states to analyzing the body parts of animals. Aristotle himself dissected hundreds of animals to understand what made them tick, and he proved to be some 2,000 years ahead of his time in recognizing that the dolphin is a mammal and not a fish. His system of classification, however, was a far cry from the ideas that developed in nineteenth-century taxonomy; rather than searching for evolutionary lines of descent, he ranked animals in order of their physical complexity.

In most aspects of his other work, Aristotle established sharp distinctions between his own

ideas and those of his teacher, Plato (427?–347 B.C.). For example, Aristotle rejected Plato's position that every idea we can conceive is but a dim reflection of an essential concept—for example, that our idea of "red" is only a shadowy copy of the perfect notion of "redness." Yet in his taxonomy, Aristotle seemed to hark back to his days as Plato's star pupil. The Aristotelian principles of classification were governed by the idea that there are constant, unchanging "essences" that unite classes of organisms. This idea of essences is completely at odds with the empirical (experience-based) mentality that governs taxonomy today. Nonetheless, for two millennia, Aristotelian ideas represented the cutting edge in taxonomy and much else.

THE MIDDLE AGES AND RENAISSANCE. After Aristotle and his brilliant student Theophrastus (371?–287? B.C.), the father of botany, there would be no Western biological theorists of remotely comparable stature until the time of the Renaissance. In the meantime, taxonomy, as with so many other areas of learning in Europe, declined badly. During the Middle Ages, what passed for taxonomic writings consisted primarily of bestiaries, books full of fanciful and imaginary creatures, such as the unicorn. The first signs of scientific reawakening in the biological sciences in general, and taxonomy in particular, came with plant and animal catalogues by such great medieval scholars as Peter Abelard (1079–1142) and Albertus Magnus (*ca.* 1200–1280). Even so, their work consisted primarily of summations of existing Aristotelian knowledge rather than new contributions.

In the sixteenth century, the Swiss scientist Konrad von Gessner (1516–1565) wrote *Historia animalium* (1551–1558), a groundbreaking work that included descriptions of many animals never before seen by most Europeans. Gesner also denounced the practice of including fictitious animals in bestiaries. Around the same time, the discoveries of new plant and animal species in the New World began to point up the need for a taxonomy that went beyond Aristotle's. The first scholar of the modern era to attack this problem was the Italian botanist Andrea Cesalpino (1519–1603), but nearly two centuries would pass before the development of a workable classification system.

LINNAEUS AND OTHERS. The man who revolutionized taxonomy was born Carl von Linné but adopted the Latinized name Carolus Linnaeus. Even that late in scientific history, scholars still wrote chiefly in Latin, not because they were trying to adhere to tradition but because it remained a common language between educated people of different countries. Thus, Linnaeus's great work, which he first published in 1737 but revised numerous times, was named *Systema naturae,* or "The Natural System." Thanks to Linnaeus, Latin became enshrined permanently as the language of taxonomy the world over, but this was far from his only accomplishment.

It was Linnaeus who introduced binomial nomenclature, in a 1758 revision of his *Systema,* and also Linnaeus who established several of the obligatory rankings. Moreover, he instituted the first taxonomic keys, and his system, first applied in botany, became accepted in the zoological community as well. Others, including Baron Georges Cuvier (1769–1832), Michel Adanson (1727–1806), and Comte Georges Buffon (1707–1788), refined Linnaeus's system, but he stands as a towering figure in the discipline.

Later, the French natural philosopher Jean Baptiste de Lamarck (1744–1829) proposed a distinction between vertebrates, or animals with spinal columns, and invertebrates. Today this distinction is not considered as useful as it once was, since it is lopsided—that is, there are nine times as many invertebrates as vertebrates in the animal kingdom—but at the time, it represented an advancement. Less questionable were the distinctions introduced in 1866 by the German biologist Ernst Haeckel (1834–1919) between plants, animals, and single-cell organisms. As Haeckel reasoned, at the level of unicellular organisms, distinctions between plant and animal really make no sense.

DARWIN AND THE TWENTIETH CENTURY. By far the most influential figure in taxonomy during the nineteenth century was the man also recognized as the most influential figure in all of biology during that era: Darwin. Whereas Linnaeus had retained the Aristotelian focus on the "essence" of the animal's features, Darwin swept away such notions and, in his *Origin of Species* (1859), proposed that the "community of descent" is "the one known cause of close similarity in organic beings" and therefore the only reasonable basis for taxonomic classification systems. As result of Darwin's work, taxonomists

became much more oriented toward the representation of phylogeny in their classification systems. Therefore, instead of simply naming and cataloguing species, modern taxonomists also try to construct evolutionary trees showing the relationships between different species.

Since Darwin's time, taxonomy has seen numerous innovations, including the introduction of cladistics by Hennig and of numerical taxonomy by Sokal and Sneath. Taxonomists today make use of something unknown at the time of Darwin: DNA (deoxyribonucleic acid, a molecule that contains genetic codes for inheritance), which provides a wealth of evidence showing relationships between creatures. For example, a comparison of human and chimpanzee DNA reveals that we share more than 98% of the same genetic material, indicating that the two lines of descent are related more closely than either is to apes.

The Five Kingdoms

There are several taxonomic systems, distinguished in part by the number of different kingdoms that each system recognizes. The system used in this book is that of five kingdoms, listed here, which is the result of modifications by the American biologists Lynn Margulis (1938–) and Karlene V. Schwartz (1936–) to the work of earlier taxonomists. (It should be noted that biologists are increasingly using a system of six kingdoms under three domains: eubacteria, arachaea, and eukaryotes. For the sake of simplicity, however, the five-kingdom system is used here.) These five kingdoms are as follows:

Monera: bacteria, blue-green algae, and spirochetes (spiral-shaped, undulating bacteria). Members of this kingdom, consisting of some 10,000 or more known species, are single-cell prokaryotes, meaning that the cell has no distinct nucleus. Some researchers have divided Monera into Eubacteria, or "true" bacteria, and Archaebacteria, which are bacteria-like organisms capable of living in extremely harsh and sometimes anaerobic (oxygen-lacking) environments, such as in acids, saltwater, or sewage.

Protista (or Protoctista): protozoans, slime molds (which resemble fungi), and algae other than the blue-green variety. Made up of more than 250,000 species, this kingdom is distinguished by the fact that its members are single-cell organisms, like the Monera. These organisms, however, are eukaryotes, or cells with a nucleus as well as organelles (sections of the cell that perform specific functions).

Fungi: fungi, molds, mushrooms, yeasts, mildews, and smuts (a type of fungus that afflicts certain plants). Fungi are multicellular, consisting of specialized eukaryotic cells arranged in a filamentous form (that is, a long, thin series of cells attached either to one another or to a long, thin cylindrical cell). There are some 100,000 varieties of fungi.

Plantae: plants, of which there are upward of 250,000 species. Although *plant* is a common term, there is no universally accepted definition that includes all plants and excludes all nonplants. One of the most important characteristics of plants is the fact that they receive their nutrition almost purely through photosynthesis. Beyond the plant kingdom, this is true only of a few protests and bacteria. (For the most part, the three lower kingdoms obtain nutrition through absorption.) Other characteristics of plants include the fact that they are incapable of locomotion; have cells that contain a form of carbohydrate called cellulose, making their cell walls more or less rigid; are capable of nearly unlimited growth at certain localized regions (unlike most animals, which have set numbers of limbs and so forth); and have no sensory or nervous system.

Animalia: animals, of which there are more than 1,000,000 species. Like plants, animals are characterized by specialized eukaryotic cells, but also like plants, the comprehensive definition of *animal* is not as obvious as one might imagine. Mobility, or a means of locomotion, is not a defining characteristic, since sponges and corals are considered animals. The principal difference between animals and plants is at the cellular level: animals either lack cells walls entirely or have highly permeable walls, unlike the cellulose cell walls in plants. Another defining characteristic of *animal* is that they obtain nutrition by feeding on other organisms. Additionally, animals usually have more or less fixed morphological characteristics and possess a nervous system. The fact that most animals are mobile helps account for the large number of animal species compared with those of other kingdoms; over the course of evolutionary history, mobility brought about the introduction of animals to a wide range of environments, which required a wide range of adaptations.



A diver inside a barrel sponge along a coral reef in the Caribbean. Mobility, or a means of locomotion, is not a defining characteristic of kingdom Animalia; indeed, sponges and corals are considered animals. *(© Jeffrey L. Rotman/Corbis. Reproduced by permission.)*

Space does not permit a discussion of the various phyla, let alone the smaller divisions, in anything like the detail we have accorded to kingdoms. Furthermore, the distinctions among most phyla, apart from higher animals and some plants, makes for rather dry reading to a nonscientist. These divisions are discussed in further detail, however, within the essays Species and

Speciation. The latter essays also address the definition of species, a great and continuing challenge that faces taxonomists.

TAXONOMY IN ACTION

Two stories reported in *National Geographic News* online (see "Where to Learn More") in 2001 and 2002 illustrate the fact that scientific classification is an ongoing process, and that the world of taxonomy is frequently home to controversies and surprises. Lee R. Berger of the *Geographic* reported the first story, on December 17, 2001, under the heading "How Do You Miss a Whole Elephant Species?" As it turns out, there are not just two species of elephant, as had long been believed, but three.

In addition to the Asian elephant (*Elephas maximus*) scientists had long recognized the African savanna elephant, or *Loxodonta africana,* as a second species. However, DNA testing (see Genetics and Genetic Engineering) in 2001 revealed a second African variety, *Loxodonta cyclotisare* or the African forest elephant, formerly believed to constitute merely a subspecies.

The news was not entirely new: as early as a century prior to the announcement of the "new" species, zoologists had begun to suspect that the forest elephant was a separate grouping distinguished by a number of characteristics. For example, the forest elephant is physically smaller, with males seldom measuring more than 8 ft. (2.5 m) at the shoulder, as compared to 13 ft. (4 m) for a large savanna male. Additionally, ivory samples confiscated from poachers or illegal hunters have revealed that the material in the tusks of the forest variety is pinker and harder than that of its savanna counterpart.

Recognition of the third elephant species followed years of argument as to whether the two African varieties are capable of interbreeding, which would indicate that they are not separate species. That debate was rendered moot by the DNA studies, which showed that the African forest and savanna elephants are less closely related genetically than are lions and tigers, or horses and zebras.

A "NEW" INSECT ORDER. The identification of the forest elephant in 2001 was a major taxonomic event, inasmuch as the elephant itself is a large and commonly known creature. However, it was still a matter only of identifying a new species, whereas in 2002, for the first time in 87 years, taxonomists identified an entirely new insect order. Actually, the order consists of a single known species, but this one is so different from others that it must be grouped separately. Discovered in Namibia, in southwestern Africa, the creature was given the nickname "the gladiator" in honor of the Academy Award-winning 2000 film of that name.

Entomologist Oliver Zompro of the Max Planck Institute of Limnology in Plön, Germany, described the creature as "a cross between a stick insect, a mantid, and a grasshopper," according to the *Geographic.* Because its first body segment is the largest, it is distinguished from a stick insect, whereas it differs from a mantid inasmuch as it uses both fore and mid-legs to capture prey. And while it looks like a grasshopper, "the gladiator" cannot jump.

Measuring as much as 1.6 in. (4 cm) long, the insect, whose order is designated as *Mantophasmatodea,* is a carnivorous, nocturnal creature. Its discovery raised the number of known insect orders to 31, a discovery that Piotr Naskrecki, director of the Conservation International Invertebrate Diversity Initiative, compared to finding a mastodon or saber-toothed tiger. Colorado State University ecologist Diana Wall described the discovery as "tremendously exciting" and told the *Geographic,* "This new order could be a missing link to determining relationships between insects and other groups. ... Every textbook discussing the orders of insects will now need to be rewritten."

WHERE TO LEARN MORE

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KEY TERMS

ALGORITHM: A specific set of step-by-step procedures for computing answers to a mathematical problem.

ANALOGOUS FEATURES: Morphological characteristics of two or more taxa that are superficially similar but not as a result of any common evolutionary origin. For example, birds, bats, and butterflies all have wings, but this is not because they are closely related. Compare with *homologous features.*

BINOMIAL NOMENCLATURE: A system of nomenclature in biological taxonomy whereby each type of plant or animal is given a two-word name, with the first name identifying the genus and the second the species. Genus name is always capitalized and abbreviated after the first use, and species name is lowercased. Both are always shown in italics; thus, *Homo sapiens* and, later in the same document, *H. sapiens.*

BIOME: A large ecosystem (community of interdependent organisms and their inorganic environment) characterized by its dominant life-forms. There are two basic varieties of biome: terrestrial, or land-based, and aquatic.

CLADISTICS: A system of taxonomy that distinguishes taxonomic groups or entities (i.e., taxa) on the basis of shared derived characteristics, hypothesizing evolutionary relationships to arrange these in a treelike, branching hierarchy. Cladistics is one of several competing approaches to taxonomic study.

CLASS: The third most general obligatory of the taxonomic classification ranks, after *phylum* but before *order.*

CLASSIFICATION: A very broad term, with application far beyond the biological sciences, that refers to the act of systematically arranging ideas or objects into categories according to specific criteria. A more specific term is *taxonomy.*

EUKARYOTE: A cell that has a nucleus as well as organelles (sections of the cell that perform specific functions) bound by membranes.

FAMILY: The third most specific of the seven obligatory ranks in taxonomy, after *order* but before *genus.*

FUNGI: One of the five kingdoms of living things, consisting of multicellular eukaryotic cells arranged in a filamentous form (that is, a long, thin series of cells attached either to one another or to a long, thin cylindrical cell.) Fungi include "true" fungi, molds, mushrooms, yeasts, mildews, and smuts (a type of fungus that afflicts certain plants).

GENUS: The second most specific of the obligatory ranks in taxonomy, after *family* but before *species.*

HOMOLOGOUS FEATURES: Morphological characteristics of two or more taxa that indicate a common evolutionary origin, even though the organisms may differ in terms of other morphological features. An example is the pentadactyl limb, common to many birds and most mammals (e.g., the human's four fingers and thumb), which indicates a common ancestor. Compare with *analogous features.*

KINGDOM: The highest or most general ranking in the obligatory taxonomic system. In the system used in this book, there

KEY TERMS CONTINUED

are five kingdoms: Monera, Protista, Fungi, Plantae, and Animalia.

MONERA: One of the five kingdoms of living things, consisting of single-cell prokaryotes, including bacteria, blue-green algae, and spirochetes (spiral-shaped undulating bacteria that may cause such diseases as syphilis).

MORPHOLOGY: Structure or form, or the study thereof.

NOMENCLATURE: The act or process of naming, or a system of names—particularly one used in a specific science or discipline. See also *binomial nomenclature.*

NUMERICAL TAXONOMY: An approach to taxonomy in which specific morphological characteristics of an organism are measured and assigned numerical value, so that similarities between two types of organism can be compared mathematically by means of an algorithm. Numerical taxonomy also is called *phenetics.*

OBLIGATORY TAXONOMY (OR OBLIGATORY HIERARCHY): The seven taxonomic ranks by which all species must be identified, whether or not they also are identified according to nonobligatory categories, such as subphylum, cohort, or tribe. These ranks are *kingdom, phylum, class, order, family, genus,* and *species.*

ORDER: The middle of the seven obligatory ranks in taxonomy, more specific than *class* but more general than *family.*

PHENETICS: Another name for *numerical taxonomy.*

PHOTOSYNTHESIS: The biological conversion of light energy (that is, electromagnetic energy) from the Sun to chemical energy in plants. In this process carbon dioxide and water are converted to sugars.

PHYLOGENY: The evolutionary history of organisms, particularly as that history refers to the relationships between lifeforms, and the broad lines of descent that unite them.

PHYLUM: The second most general of the obligatory taxonomic classification ranks, after *kingdom* and before *class.*

PROKARYOTE: A cell without a nucleus.

PROTISTA (OR PROTOCTISTA): One of the five kingdoms of living things, consisting of single-cell eukaryotes. Protista include protozoans, slime molds (which resemble fungi), and algae other than the blue-green variety.

SPECIES: The most specific of the seven obligatory ranks in taxonomy.

SYSTEMATICS: The science of classifying and studying organisms with regard to their natural relationships.

TAXON: A taxonomic group or entity.

TAXONOMY: The area of the biological sciences devoted to the identification, nomenclature, and classification of organisms according to apparent common characteristics. The word *taxonomy* also can be used more generally to refer to the study of classification or to methods of classification (e.g., "the taxonomy of Dickens's characters.")

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SPECIES

CONCEPT

One of the challenges that faces a student of the biological sciences is the seemingly endless array of unfamiliar terms that one must learn. It is a relief to come across a relatively familiar one, such as species. Although it has a scientific sound to it, the word has entered everyday language, such that when people use it, most everyone understands what is meant. Or do they? As it turns out, there is no hard and fast definition for the word. Nonetheless, it is easy enough to find examples of species, since there are many millions of them in five kingdoms of living things—a product of a phenomenon know as *speciation,* whereby evolutionary lines of descent diverge and new species are created. In the world today, there are many interesting groups of species, distinguished neither by evolutionary line nor by taxonomy but instead by the ways in which they interact with their environments. Among these groups are endangered species, of whose existence most people are aware, owing to the spread of the environmentalist message through media and entertainment outlets since the early 1970s. Less familiar is another broad group that in many cases threaten humans: introduced or invasive species.

HOW IT WORKS

Taxonomy in Brief

The concept of species falls under the heading of taxonomy, the area of the biological sciences devoted to the identification, naming, and classification of living things according to apparent common characteristics. Taxonomy is discussed in detail within the essay on that subject, but to appreciate the topic of species in context, it is helpful to have at least some knowledge of the larger subject. At one time taxonomists were concerned most with the morphological characteristics (i.e., the structure or form) of organisms as a basis for classifying many species within a larger grouping. Today, however, shared evolutionary lineage is much more important than morphological features in determining whether taxa (plural of *taxon,* meaning a taxonomic group or entity) can be classed together. Organisms may be linked closely in terms of evolutionary lines of descent but differ in a particular morphological aspect as a result of the adaptive changes that accompany natural selection. The latter, a key concept in the theory of evolution put forward by the English naturalist Charles Darwin (1809–1882), is a process whereby some organisms thrive and others perish, depending on their degree of adaptation to a particular environment.

It is therefore possible for organisms in a particular environment to develop a common adaptive mechanism through generations of natural selection, even though those organisms themselves are not related to fish closely in terms of evolutionary line of descent. Thus, whales and dolphins, mammals that live underwater, evolved the ability to swim just as well as fish, but that does not mean they are connected closely. Conversely, organisms may be close, or relatively close, in terms of evolutionary lines of descent yet differ in significant morphological features. To use the whale and dolphin example again, these creatures are classified as mammals owing to certain particulars (discussed later), but they differ from the vast majority of mammals in that they have no legs. They do, however, have four appendages, just like the rest of the mammalian class; as a result of natural selection, however,

theirs ceased to operate as legs (an encumbrance for life in the water) a long time ago, and today they function instead as fins.

OBLIGATORY RANKS

The classification system used today is an outgrowth of a system developed by the Swedish botanist Carolus Linnaeus (1707–1778) in the 1730s. The realms of zoology and botany, areas of biology devoted to the study of animal and plant life, respectively, differ somewhat with regard to their classification systems, but both use international codes of nomenclature with roots in the Linnaean system. There are many possible ranks of classification, but only seven are obligatory, meaning that all species must be assigned a place in these groupings. The obligatory ranks are listed here. The entire list of rankings, including versions of obligatory ranks with such prefixes as *sub-, super-,* and *infra-,* as well as such additional ranks as cohort or tribe, are given in Taxonomy. Note the difference between the zoological and botanical names for the second rank.

Obligatory Taxonomic Ranks

- Kingdom
- Phylum (*Division* in botany)
- Class
- Order
- Family
- Genus
- Species

As discussed in Taxonomy, this book uses a system of five kingdoms, whose characteristics are defined in that essay. Even at the level of kingdom, not everything is delineated precisely (see the discussion in Taxonomy), and there are significant areas of dispute. For example, some taxonomic systems include viruses. Because viruses are not cellular in structure and are not universally regarded as true organisms, however, they are not included in the five-kingdom system used here.

Below the level of kingdom, definitions become even more difficult. Organisms are grouped into phyla on the basis of body plan or organization, but there is no regular pattern for grouping within the smaller categories. For example (as noted later herein), humans are placed within their particular phylum and subphylum on the basis of their spinal columns and overall internal bone structure, but those specifics play no significant role in categorizing them within any of the more specific groupings to which they belong. Furthermore, the generic definitions of the categories—for example, *class* as opposed to class Mammalia, class Insecta, or some other class in the taxonomic system—are purely relative. In other words, class is simply the obligatory rank that is more specific than phylum but more general than order.

DESIGNATING A SINGLE SPECIES WITHIN THE RANKS. When preparing an outline for a paper, students are taught that no topic should have only one subheading; instead, that solitary subheading should be moved up one level. Such rules do not apply in taxonomy, and it is not necessary that there be more than one subgroup within a larger group. For example, there might be only one class in a phylum. Taxonomists use detailed definitions to single out particular groups, such as class Mammalia. The following list shows the placement of humans within the larger taxonomic universe, along with brief explanations of a few (though far from all) characteristics that define each group.

- Kingdom Animalia: Multicell eukaryotic (that is, possessing cells with a nucleus and specialized compartments called organelles) organisms that obtain their nutrition solely by feeding on other organisms. (Other defining characteristics of Animalia are discussed in Taxonomy.)
- Phylum Chordata: Animals whose bodies, at least at some point in their life cycles, include a rudimentary internal skeleton with a stiff supporting rod known as a notochord. All chordates at some point also breathe through gills (in the case of a human, while still in the womb). Other characteristics set apart chordates, including a tail or the remnants of one. Humans belong to the subphylum Vertebrata, or chordates with a spinal column.
- Class Mammalia: Vertebrates that feed their young from special milk-secreting glands, known as mammae, located on the mother's body. Mammals have other distinguishing characteristics, such as a hinged lower jaw attached to the skull.
- Order Primates: A group of mammals whose characteristics may include some version of an opposable digit (e.g., the human thumb) and other features that,

while they are prevalent among most primates, are not universal to them. Not every one of these traits is exclusive to primates, a group that includes prosimians (e.g., lemurs), monkeys, apes, and humans.

- Family Hominidae: Primates noted for their erect posture, large brains, rounded skulls, small teeth, bipedal locomotion (i.e., they walk on two legs), and tendency to use language for communication. Humans are the only surviving species in the family, but extinct hominids include *Homo habilis* (about 1.6 million years ago) and *H. erectus* (about two million years ago) as well as the more distant *Australopithecus* (about eight million years ago).
- Genus *Homo*: Hominids with especially large skulls as well as the features that characterize family Hominidae. Members of this genus, which included *H. erectus* and *H. habilis* as well as *H. sapiens,* also are known for their ability to fashion precise tools.
- Species *Homo sapiens*: Members of the genus *Homo* ("man") noted for, among other things, the ability to use symbols and writing. This category includes modern humans and the extinct Cro-Magnon and Neanderthal man.

Note that the proper name of any ranking more general than species is capitalized (e.g., phylum Chordata), with species (and subspecies) names in lowercase. Genus, species, and subspecies names are rendered in italics (e.g., *Homo sapiens,* or "man the wise"), whereas proper names of the more general groupings are presented in ordinary type (e.g., class Mammalia). If the same name appears a second time in the same article, the genus name usually is abbreviated: thus, *H. sapiens.* Another important abbreviation is spp., implying several species within a genus—for example, *Quercus* spp. refers to more than one species of oak.

Taxonomy makes use of a system called binomial nomenclature, in which each species is identified by a two-word name, designating genus and species proper. Beyond the species name, there may be subspecies names: humans are subspecies *sapiens,* so our full species name with subspecies is *Homo sapiens sapiens.* Additional rules govern the inclusion of a name or an abbreviation at the end of the species or subspecies name, to recognize the person who first identified it—in this case, Linnaeus. Hence the proper full name of our species is *Homo sapiens sapiens* Linneaus, 1758.

The Mystery of Species

If one studies the delineation of humans' place in the overall taxonomic structure, one may notice that for several groupings, the defining characteristics are a bit "fuzzy around the edges." This is true even of the animal kingdom, as noted in Taxonomy: mobility and locomotion, seemingly so integral to the definition of *animal,* are not prevalent among all animal species. Given the many gray areas and areas of dispute in the larger taxonomic categories, it should come as no surprise that the smallest of the obligatory rankings, that of species, lacks a precise definition.

The most widely accepted definition of species is the one put forward by the German-born American evolutionary biologist Ernst Mayr (1904–) in the 1940s. Mayr's idea, known as the biological species concept, defines a species as a population of individual organisms capable of mating with one another and producing fertile offspring in a natural setting. Members of two different, but closely related species in some cases can mate with one another to produce *infertile* offspring, the most well-known example being the mule, a sterile hybrid produced by the union of a male donkey and a female horse.

The definition offered by the biological species concept requires qualification. While many plants and animals reproduce sexually, many more do not; *no* single-cell life-forms reproduce in this way, yet there are certainly many different and distinct species of bacteria and protozoa. Thus, a further qualification typically is added to the definition of species*:* members of the same species share a gene pool, or a total sum of genes. Genes carry information about heritable traits, which are passed from parent to offspring. Whereas the gene pool is shared by members of a species, nonmembers of that species have genes that do not belong to that gene pool. To use a rudimentary example, let's say that there is a gene pool containing genes *x, y,* and *z.* Individuals that have these genes fit within the gene pool, but an individual with gene *w* does not.

The definition of species remains challenging, with special problems raised in the area of botany. It is also sometimes possible to confuse



Inuit villagers butcher a whale. Among endangered species is the right whale, so called because whalers of the nineteenth century considered it the "right" whale to hunt: it swims slowly and close to shore and can be found and slaughtered easily. *(© Lowell Georgia/Corbis. Reproduced by permission.)*

species and race, a grouping that applies not only in the world of humans but also that of other animal and even plant species. Race is different from species inasmuch as races are not isolated genetically from one another; in other words, there are no biological barriers to interbreeding between races. (See Speciation for a discussion of the process whereby single species develop over time into more than one reproductively isolated species.)

REAL-LIFE APPLICATIONS

Endangered Species

An endangered species is any plant, animal, or microorganism that is at risk of becoming extinct or at least of disappearing from a particular local habitat. Over the course of Earth's geological history, species have become extinct naturally—sometimes in large proportions, as discussed in the context of mass extinction in Paleontology. In modern times, however, species and their natural communities are threatened mostly by human activities.

The number of endangered species worldwide is not known. In the United States—a country that, unlike most, expends considerable effort on keeping track of its endangered species—there were more than 750 species and subspecies listed by the late 1990s as endangered under the federal Endangered Species Act. Additional endangered species are being added at a rate of about 50 per year, and there is a "waiting list" of an estimated 3,500 candidate species.

Efforts at monitoring endangered species in the United States have directed a disproportionate amount of attention toward larger organisms; consequently, smaller endangered species from such groups as arthropods, mosses, and lichens have received insufficient attention. The regions of the United States with the largest numbers of endangered species are in the humid southeast and the arid southwest. These areas tend to have the unfortunate combination of unique ecological communities alongside runaway urbanization and resource development.

Overdevelopment and destruction of habitats is perhaps the most well-known ways that humans endanger the survival of species. For example, the habitat of the northern spotted owl is under threat from loggers in the Pacific North-

west (see Succession and Climax). Another threat is the introduction of new species, particularly predators, to an area that is not their natural habitat—a topic we discuss in more depth later in this essay.

HUNTING THE ESKIMO CURLEW. Another way humans threaten species is by excessive hunting. An example of a species thus threatened is the Eskimo curlew (*Numenius borealis*), a sandpiper (a type of bird) that was still abundant in North America during the nineteenth century. A large, friendly creature, it was hunted in vast numbers during its seasonal migrations over the prairies and coasts of Canada and the United States and during its winter seasons in South America. (See Migration and Navigation for more about birds' winter migrations.) The Eskimo curlew became very rare by the end of the nineteenth century, and the last time an Eskimo curlew nest was seen (1866), the guns of the Civil War were practically still smoking. The last time a scientific team collected an Eskimo curlew specimen was in 1922. It might seem that the bird is extinct, but this is not the case. Although it is extremely rare, there have been a few reliable sightings of individuals and small flocks of this species, mostly during migration in Texas and elsewhere but also in its breeding habitat in the Canadian Arctic. Once abundant, the Eskimo curlew now hangs on by a thread.

RIGHT WHALES AND BLUE WHALES. More familiar is the endangerment of whales, a cause made popular by many a "Save the Whales" bumper sticker. Among endangered animals of this group are the blue whale (*Balaenoptera musculus*) and various species from the genus *Balaena,* or right whale. The latter species gained its common name because whalers of the nineteenth century considered it the "right" whale to hunt: it swims slowly and close to shore and so could be found and slaughtered easily. In addition, it yields a large amount of oil, used for lighting lamps in the era when Herman Melville's *Moby Dick* (1851) was written. The estimated world population of right whales is currently about 2,000 individuals, much depleted from the historical high numbers; though it is now protected from whaling, it suffers an excessive mortality rate from ship collisions.

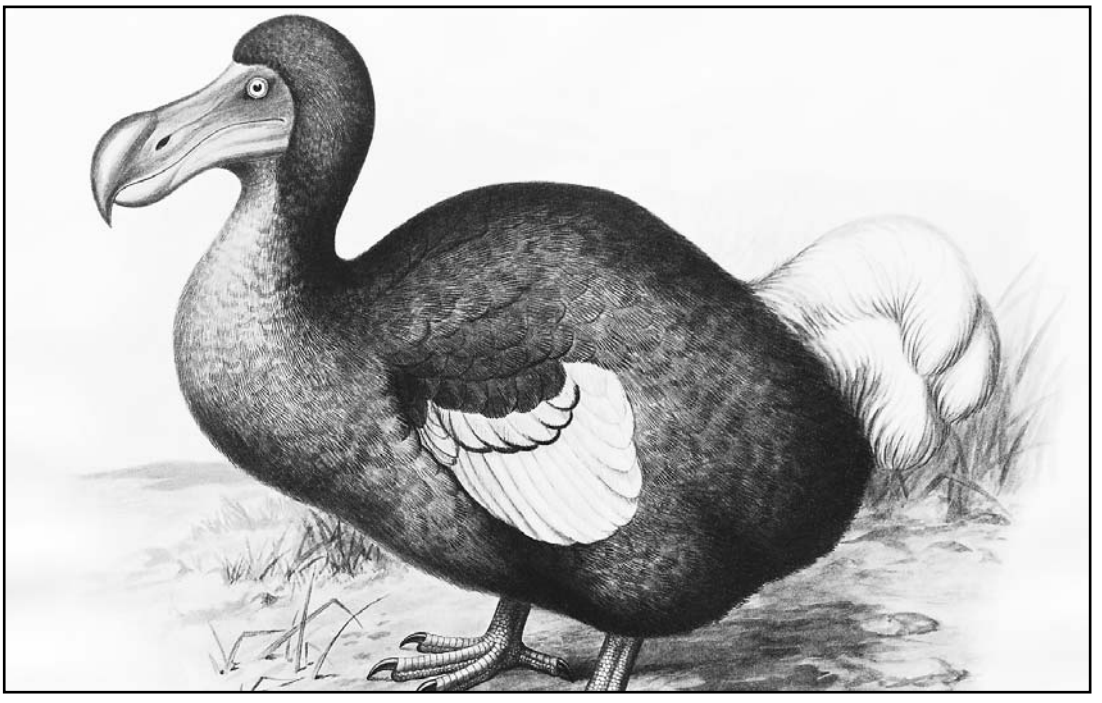
As for the blue whale, it occurs virtually worldwide, and with a typical weight of 150 tons (136 tonnes) and a length of 100 ft. (30 m), it is the largest animal ever to have lived on Earth. Because it is such a fast swimmer, it could not be hunted effectively by whalers in sailing ships. Once steam-powered ships were invented, however, these whales were taken in tremendous numbers and became endangered. Because of its precarious status, this species has not been hunted for several decades, but it remains rare and endangered.

The Fate of the Dodo

When a species becomes extinct, it is gone forever. It is like a family whose last member has died without leaving an heir, but in this case the impact is potentially much more profound. Several thousand species have become extinct as the result of human activities, mostly hunting, in the past few hundred years, and of these species perhaps none is more well known than *Raphus cucullatus,* or the dodo.

Long before the application of the term clueless in the 1990s, a person out of touch or out of step was called a *dodo.* How did the bird's name come to be a synonym for stupidity? Perhaps it is just the funny sound of the name, or perhaps it is the fact that the dodo looked a bit like a turkey, another bird name used for someone of less than exemplary capabilities. Or perhaps the application of the name *dodo* in this way carries a hint of blaming the victim—the implication that the dodo somehow played a part in its own extinction.

In fact, the dodo's only shortcoming was its inability to overcome the threat posed by an extremely dangerous predator: the human. A member of the dove or pigeon family, the dodo was flightless and lacked natural enemies until humans discovered its homeland, the Indian Ocean island of Mauritius, in the early sixteenth century. First came the Portuguese and then, in 1598, the Dutch, who made the island a colony in 1644. By 1681 the dodo had ceased to exist. Not only did sailors collect the birds for food, but introduced species, including dogs, cats, pigs, monkeys, and rats, also preyed on dodos. They were subjected to regular slaughter by sailors, but the species managed to breed and survive on the remote areas of the island for a time. After the establishment of their colony, however, Dutch



A member of the dove or pigeon family, the dodo was flightless and lacked natural enemies until humans discovered its homeland, the island of Mauritius, in the early sixteenth century. By 1681, through the effects of predation, the dodo had ceased to exist. *(© Bettmann/Corbis. Reproduced by permission.)*

settlers launched what amounted to an extermination campaign.

No part of Earth's living environment can be removed without repercussions, and the destruction of the dodo illustrates the ripple effect that occurs when one species is eliminated. As it turned out, the bird had a symbiotic relationship (see Symbiosis) with the dodo tree, or *Calvaria major,* whose fruit it ate, thus releasing the seeds to germinate. With the dodo gone, the dodo tree stopped being able to reproduce. Fortunately, it is a species with a long life, and some specimens of *C. major* continue to survive after some 300 years; when those die, however, this species, too, will be extinct.

Exotic, Introduced, and Invasive Species

An introduced species is one that has been spread to a new environment or habitat as a result of human activity. An invasive species may or may not have been spread by humans (the ones we discuss were), but as the name suggests, it threatens an aspect of the habitat to which it has been introduced. Both introduced and invasive species are examples of exotic species, or species that have been introduced to a region or continent, usually but not always through human activity.

In the case of species introduced by humans, some were introduced deliberately and were intended to improve conditions for some human activity (for example, in agriculture) or to achieve desired aesthetic results—for example, when colonists wanted to plant a flower or tree that reminded them of home. Other introductions have been accidental, as when plants were brought with soil transported as ballast in ships or insects were conveyed with timber or food.

Beneficial and harmful introductions. Some introduced species have been wildly successful. In fact, most agricultural plants and animals are introduced species: for example, wheat (*Triticum aestivum*) was originally native only to a small region of the Middle East, but it now grows virtually anywhere conditions are suitable for its cultivation. Likewise, corn, or maize (*Zea mays*), has spread far beyond its home in Central America. The domestic cow (*Bos taurus*) once lived only in Eurasia and the turkey (*Meleagris gallopavo*) only in North America, but today these species can be found throughout the world. If all introduced species were like cows and corn, or turkeys and

wheat, there would not be much cause for alarm. Many introduced species are invasive, however, and pose a wide variety of threats—threats to their environments or, in some cases, to human well-being. All manner of weeds and pests are among the nefarious roll-call of invasive species, a broad grouping that ranges from nuisances to serious dangers.

ACCIDENTAL AND DELIBERATE INTRODUCTIONS. There are more than 30,000 introduced species in the United States, and most of them enhance rather than diminish the quality of life. For example, there are the many species introduced by colonists to make them feel more comfortable in their new homes, among them, the Norway maple (*Acer platanoides*), linden (*Tilia cordata*), horse chestnut (*Aesculus hippocastanum*), and other trees as well as many exotic species of shrubs and herbaceous plants. The European settlers also introduced some species of birds and other animals with which they were familiar, such as the starling (*Sturnus vulgaris*), house sparrow (*Passer domesticus*), and pigeon, or rock dove (*Columba livia*).

These are all deliberate introductions; on the other hand, accidental introductions are more likely to be undesirable. When cargo ships from Europe did not have a full load of goods, they had to carry other heavy material as ballast, to help the vessel maintain its stability on the ocean. Early ships to the New World often used soil as ballast, and upon arriving, sailors dumped this soil near the port. In this way, many European weeds and other soil-dwelling organisms arrived in the Americas. In addition, ships have used water as ballast since the late nineteenth century, and many aquatic species have become widely distributed by this practice. This is how two major pests, the zebra mussel (*Dreissena polymorpha,* discussed later) and the spiny water flea (*Bythothrepes cederstroemii*) were introduced to the Great Lakes from European waters.

Several European weeds are toxic to cattle if eaten in large quantities, and when these plants become abundant in pastures, they represent a significant potential problem. Some examples of toxic introduced weeds in the pastures of North America include common Saint-John's-wort (*Hypericum perforatum*), ragwort (*Senecio jacobaea*), and common milkweed (*Asclepias syriaca*). Several introduced insects have become troublesome pests in forests, as is the case with the gypsy moth (*Lymantria dispar*), which has defoliated many trees since its introduction to North America from Europe in 1869.

Similarly, the introduced elm bark beetle (*Scolytus multistriatus*) has helped spread Dutch elm disease, itself caused by an introduced fungus, *Ceratocystis ulmi.* It would be interesting to note the irony inherent in this affliction, which at first glance seems to involve another apparently introduced species, the "Dutch elm." There is no such tree, however; the name refers to the fact that the disease arrived in America from Holland, probably some time after World War I. Its principal victim is the American elm, or *Ulmus americana.*

DELIBERATE AND HARMFUL INTRODUCTIONS. Not all harmful introduced species were introduced accidentally. Settlers from Europe deliberately brought pets, such as the domestic dog (*Canis familiaris*) and cat (*Felis catus*); while these pets may add greatly to the quality of human life, they can cause problems, because they are wide-feeding predators. Such creatures threaten vulnerable animals in many places, especially isolated oceanic islands. Among other predators are mongooses (family Viverridae), often introduced to get rid of snakes, as well as omnivores, such as pigs (*Sus scrofa*) and rats (*Rattus* spp.) Meat-eating animals are not the only threat: herbivores such as sheep (*Ovis aries*) and goats (*Capra hircus*) also endanger plant life in some areas as a result of overgrazing.

A particularly striking example of harmful, deliberate species introduction is the Nile perch (*Lates niloticus*). First introduced to Africa's Lake Victoria in the 1950s, it has proved an economically important food source, with a large worldwide market. The problem is that the Nile perch is an extraordinarily active predator and has brought about a tragic mass extinction of native fishes. Until the 1980s, Lake Victoria supported an extremely diverse community of more than 400 species of fish, mostly cichlids (family Cichlidae), with 90% of those species being endemic, meaning that they exist only in one area. About one-half of the endemic species are now extinct in Lake Victoria because of predation by the Nile perch, although some species survive in captivity, and a few are still in the lake.

KILLER BEES, ZEBRA MUSSELS, AND KUDZU. Three notable examples of invasive species in America are



The Africanized, or "killer," bee is one example of an invasive species. These bees have no more venom than domesticated honeybees, but they attack more quickly and in great numbers and have spread throughout much of South and Central America, Texas, and California. *(© S. Camazine/Photo Researchers. Reproduced by permission.)*

Africanized honeybees (*Apis mellifera scutellata*), better known as "killer bees"; the zebra mussel (*Dreissena polymorpha*); and kudzu (*Pueraria lobata*). The first "killer" bees were released accidentally by a Brazilian bee breeder in 1957. These aggressive insects have no more venom than domesticated honeybees (another *A. mellifera* subspecies, which is also an Old World import), but they attack more quickly and in great numbers. Interbreeding with resident bees and sometimes traveling with cargo shipments, Africanized bees have spread at a rate of up to 200 mi. (320 km) a year and now threaten humans, fruit orchards, and domestic bees throughout much of South and Central America and north to Texas and California.

The zebra mussel was introduced to the Great Lakes in about 1985 in ballast water dumped by a ship or ships arriving from Europe. It colonizes any hard surface, including rocks, wharves, industrial water-intake pipes, and the shells of native bivalve mollusks. A bean-sized female zebra mussel can produce 50,000 larvae (an immature form of an animal) in a single year. Growing in masses with up to 70,000 individuals per square foot, zebra mussels clog pipes, suffocate native clams, and destroy the breeding habitats of other aquatic animals. These invaders have placed a great burden not only on the environment but also on the economy of the Great Lakes region: area industries spend hundreds of millions of dollars annually to unclog pipes and equipment.

Kudzu is an integral part of culture in the southern United States, but it originated in Japan and did not arrive on American shores until 1876. In that year, numerous foreign governments sent exhibits to the Centennial Exposition, held in Philadelphia to honor the country's 100th birthday. Two generations later, during the Great Depression, the U.S. Soil Conservation Service began promoting the use of kudzu for erosion control.

At a time when work was scarce, young men in the government-sponsored Civilian Conservation Corps (CCC) earned a living by planting kudzu throughout the South. The federal government paid farmers as much as $8.00 an acre—a fabulous sum at the time—to plant kudzu fields. Before another generation had passed, in 1953, the federal government stopped promoting the use of kudzu. In 1972, just four years shy of a

KEY TERMS

BINOMIAL NOMENCLATURE: A system of nomenclature in biological taxonomy whereby each type of plant or animal is given a two-word name, with the first name identifying the genus and the second the species. The genus name is always capitalized and abbreviated after the first use, and the species name is lowercased. Both are always shown in italics—thus, *Homo sapiens* and, later in the same document, *H. sapiens.*

CLASS: The third most general of the obligatory taxonomic classification ranks, after *phylum* but before *order.*

DNA: Deoxyribonucleic acid, a molecule in all cells, and many viruses, containing genetic codes for inheritance.

ENDANGERED SPECIES: Any plant, animal, or microorganism that is at risk of becoming extinct or at least of disappearing from a particular local habitat.

ENDEMIC SPECIES: Species that exist in only one geographic region.

EUKARYOTE: A cell that has a nucleus as well as organelles (sections of the cell that perform specific functions) bound by membranes.

EXOTIC SPECIES: Species that have been introduced to a region or continent, usually but not always through human activity. See also *introduced species* and *invasive species.*

EXTINCTION: A condition in which all members of a taxon have ceased to exist.

FAMILY: The third most specific of the seven obligatory ranks in taxonomy, after *order* but before *genus.*

GENE: A unit of information about a particular heritable (capable of being inherited) trait that is passed from parent to offspring, stored in DNA molecules called *chromosomes.*

GENE POOL: The sum of all the genes shared by a population, such as that of a species.

GENUS: The second most specific of the obligatory ranks in taxonomy, after *family* but before *species.*

HYBRID: The product of sexual union between members of two species or other smaller and less genetically separate groups, such as two races. In the case of species hybrids, the process of hybridization involves genetic abnormalities that lead in most cases to sterility.

century after its first introduction, kudzu was officially declared a weed by the U.S. Department of Agriculture.

Obviously, something had gone wrong. The problem was that kudzu grew *too* well—so fast, in fact, that in the minds of many southerners, it began to possess some sort of mystical significance. This preoccupation with kudzu is reflected in the work of several Georgians, whose state has been particularly afflicted with the vine. There is the poem "Kudzu" by James Dickey as well as the cover of *Murmur,* the music group R.E.M.'s 1983 debut, which features a photograph of a kudzu-covered railroad trestle near the group's hometown of Athens.

Kudzu covered more than railroad tracks, and in the mid–twentieth century, it began to seem as though it would cover the entire South with its tangled vines. The plant is capable of growing by as much as 1 ft. (0.3 m) per day during the summer and can cover virtually anything that is not moving. Over the course of a good

KEY TERMS CONTINUED

INTRODUCED SPECIES: A species that has been spread to a new environment or habitat, whether deliberately or accidentally, as a result of human activity. Introduced species, like invasive species, are considered exotic species.

INVASIVE SPECIES: An exotic species that threatens some aspect of the habitat to which it has been introduced.

KINGDOM: The highest or most general ranking in the obligatory taxonomic system. In the system used in this book there are five kingdoms: Monera, Protista, Fungi, Plantae, and Animalia.

MORPHOLOGY: Structure or form, or the study thereof.

NATURAL SELECTION: The process whereby some organisms thrive and others perish, depending on their degree of adaptation to a particular environment.

NOMENCLATURE: The act or process of naming or a system of names—particularly one used in a specific science or discipline. See also *binomial nomenclature.*

ORDER: The middle of the seven obligatory ranks in taxonomy, more specific than *class* but more general than *family.*

PHYLUM: The second most general of the obligatory taxonomic classification ranks, after *kingdom* and before *class.*

PROKARYOTE: A cell without a nucleus.

RNA: Ribonucleic acid, the molecule translated from DNA in the cell nucleus, the control center of the cell, that directs protein synthesis in the cytoplasm, or the space between cells.

SPECIATION: The divergence of evolutionary lineages and creation of new species.

SPECIES: The most specific of the seven obligatory ranks in taxonomy. Species often are defined as a population of individual organisms capable of mating with one another and producing fertile offspring in a natural setting. Also, members of the same species share a gene pool.

TAXON: A taxonomic group or entity.

TAXONOMY: The area of the biological sciences devoted to the identification, nomenclature, and classification of organisms according to apparent common characteristics.

year, kudzu can grow by as much as 60 ft. (20 m), and it has proved impervious to many herbicides. One herbicide used in Auburn, Alabama, actually made it grow better! Thanks to the development of better chemical treatments, and the use of grazing animals, such as goats, kudzu no longer is perceived as such a great threat. Additionally, various entrepreneurs and scientists have set out to make use of the vine in weaving baskets or in preparing foods and medicines. Ground kudzu root, called *kuru,* has long been used in foods and medications in China and Japan.

One might wonder why Japan is not covered in kudzu and why kudzu is not crawling up the Great Wall of China. The answer is more than a little interesting from a biological standpoint. When kudzu was transplanted to America, it was taken out of its native environment and thus away from the local insects that threatened its growth. In its new home there were no threats to its spread, and with no obstacles in its way, it began to take over

the South. (For more about the development of species, see Speciation. See also the discussion of keystone and indicator species in Food Webs.)

WHERE TO LEARN MORE

All Species Foundation (Web site). <http://www.all-species.org/>.

"Endangered Species on EE-Link." EE-Link (Environmental Education Link), North American Association for Environmental Education (Web site). <http://eelink.net/EndSpp/>.

Integrated Taxonomic Information System (ITIS), United States Department of Agriculture (Web site). <http://www.itis.usda.gov/>.

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SPECIATION

CONCEPT

One of the defining characteristics of a species is its reproductive isolation: the fact that among animals and plants that reproduce sexually, it is impossible for members of two different species to mate and produce fertile offspring. Speciation is the process whereby a single species develops over time into two distinct, reproductively isolated species. It is one of the key evolutionary processes and is responsible for the diversity of life that exists on Earth. In the following essay we explore not only the basic facts of speciation and biological diversity but also an example of adaptive radiation, in the form of the wide range of species within the mammalian order.

HOW IT WORKS

Species and Speciation

The concept of species, discussed in the article devoted to that subject, is an extraordinarily complex one. Owing to limitations of space, that essay only hints at the many details, the competing schools of thought, and the varying definitions of *species.* Likewise, in the present context, it is possible to examine the concept of speciation only in the most cursory fashion. In addition to consulting the essay on Species for more information, the reader is encouraged to review the article on Taxonomy.

Taxonomy is the area of the biological sciences devoted to the identification, nomenclature, and classification of organisms according to apparent common characteristics. It uses a wide array of specialized rankings for grouping animals, but only seven of them are essential to most biology students. These seven, known as the obligatory hierarchy, are kingdom, phylum, class, order, family, genus, and species. In the case of mammals, it is also useful to refer to subphylum, which in this case is Vertebrata (see the classification of humans in Species), but for the most part it is enough for the beginning student to attain at least some mastery of the obligatory ranks.

Note that species is the most specific of these ranks, which is fitting, because *species* and *specific* come from the same Latin root, *specie,* or "kind." Nonetheless, it is difficult to define species beyond a reference to its place among the categories of the obligatory taxonomy. According to the biological species concept, discussed briefly in Species, a species is any population of individual organisms capable of mating with one another and producing fertile offspring in a natural setting. This is far from the only definition, however.

INTERSPECIFIC MATING. Occasionally, it is possible to produce an infertile hybrid, such as a mule, which is created by the mating of a male donkey and a female horse, or a hinny, the product of the less common union between a male horse and a female donkey. The infertility is due to genetic disorders that arise when mating takes place between distinct species, and even this imperfect product is possible only by mating two species that are very closely related. Donkeys and horses, for instance, both belong to family Equidae, which makes them very closely connected.

In the taxonomic ranking of humans, this would be equivalent to a human mating with a fellow hominid, or member of family Hominidae. If the long-extinct genus *Australopithecus* were



A species is a population of individual organisms capable of mating with one another and producing fertile offspring. Occasionally, it is possible to produce an infertile hybrid, such as a mule, through the mating of a male donkey and a female horse. *(© D. Robert & Lori Franz/Corbis. Reproduced by permission.)*

still around, it is not inconceivable that humans could mate with them and produce at least sterile offspring. Of course, it is unlikely that many humans would want to mate with *Australopithecus,* the most famous example of which was named "Lucy" after the Beatles' song "Lucy in the Sky with Diamonds." Standing about 3.5-5 ft. (1–1.5 m) tall, *Australopithecus* was very close in appearance to a modern ape who lived about four million years ago.

All of humans' close relatives are extinct, and today our nearest relatives are members of the order Primates: apes, monkeys, and marsupials. It is impossible to imagine a human mating with one of these animals and producing offspring of any kind. Likewise, it is extremely unlikely that a horse or donkey could mate with a tapir or rhinoceros, which are about as distant in relation to them as other primates are to us. (These species all belong to the order Perissodactyla, herbivorous mammals possessing either one or three hoofed toes on each hind foot. We discuss this group, along with all other mammalian orders, later in this essay.)

The problem of defining species. Although the biological species concept is accepted widely, it has its shortcomings, not least of which is the fact that not all species reproduce sexually. Although sexual reproduction is the case with a wide array of animals and even plants, quite a few organisms reproduce by some asexual means: for example, single-cell organisms reproduce by splitting.

Among the competing definitions of species is the phenetic (or morphological) species concept, which relies in part on common sense. According to the phenetic species concept, a species is the smallest possible population of organisms that consistently and continually remains distinct and distinguishable by ordinary methods of observation. There are also a variety of definitions that fall under the heading "phylogenetic species concepts," all of which maintain in one way or another that taxonomic classifications should incorporate the most widely recognized hypotheses regarding the evolutionary lines of descent that produced the organisms in question.

The Process of Speciation

Clearly, there is no hard and fast definition of species, but in general terms, everyone who has some familiarity with the concept has at least a basic knowledge of what does and does not qualify as a species. We will leave finer distinctions to trained taxonomists and other biologists and move on to a fact regarding which there is no disagreement: a wide array of species exists in the world today. Some estimates calculate the number of species in the five kingdoms—animals, plants, monerans, protista, and fungi (see Taxonomy for a very brief identification of each)—at about 1.5 million.

This is only the number of identified species, however. Other figures, based on the probable numbers of unidentified species in the world, put the sum total in the tens of millions. Whatever the case, it is obvious that over the course of evolutionary history (discussed in Evolution and Paleontology), there has been a widespread adaptive radiation—that is, a diversification of species as a result of specialized adaptations by particular populations of organisms.

Speciation events are described as either allopatric or sympatric. Allopatric ("different places") speciation occurs when a population of organisms is divided by a geographic barrier, a great example being the division of squirrel species caused by the formation of the Grand Canyon (see Evolution). Another example is the speciation of the black-throated green warbler, which today consists of one species in the eastern United States, along with three others in the western part of the country. Some scientists speculate that there may once have been a single species of black-throated green warbler, whose population was split by the formation of a glacier during the Pleistocene epoch. The latter was the period of the last ice age, which ended about 10,000 years ago, but the end of the ice age was a slow process. It may be that glaciers, formed in the latter part of that time, helped to separate what became three different western species.

Species share the same gene pool, or the sum of all genetic codes possessed by members of that species. The isolation of two populations slowly results in differences between gene pools, until the two populations are unable to interbreed either because of changes in mating behavior or because of incompatibility of the DNA between the two populations. (Deoxyribonucleic acid, or DNA, contains genetic codes for inheritance. See Genetics for more on this subject.) More rare than allopatric speciation, sympatric ("same place") speciation happens when a group of individuals becomes reproductively isolated from the larger population of the original species. This type of speciation typically results from mutation, or alterations in DNA that result in a genetic change.

Studies of three-spined sticklebacks, a variety of freshwater fish, in British Columbia have revealed what appears to be a fascinating example of sympatric speciation. Evolutionary biologist Dolph Schluter and others have discovered that the region contains two species of stickleback, one with a large mouth that feeds on large prey close to shore, the other with a small mouth that feeds on plankton in open water. Both species jointly inhabit five different lakes. Through DNA analysis, scientists have determined that the lakes were colonized independently by common marine ancestors, meaning that the process of sympatric speciation between the two varieties had to have occurred independently at least five times. This seems to indicate a situation of competition for resources that favored stickleback species at either extreme of size, as opposed to those of medium size and medium-sized mouths.

RATE OF EVOLUTIONARY CHANGE. Closely tied to speciation is the rate of evolutionary change, or the speed at which new species arise. This is a long process, one that is usually not observable within a human lifetime or even the span of many lifetimes, though bacteria at least have shown some evolutionary change in their growing resistance to antiobiotics (see Infection). DNA analysis (see Genetics and Genetic Engineering for more about DNA) has been used to examine the rate of evolutionary change. To perform such analysis, it is necessary first to determine the percentage of similarity between the organisms under study: the greater the similarity, the more recently the organisms probably diverged from a common stock. Data obtained in this manner then must be corroborated by information obtained from other sources, such as the fossil record and comparative anatomy studies.

At certain times the rate of evolutionary change can be very rapid, leaving little fossil evidence of intermediate forms, a phenomenon known as *punctuated equilibrium.* This is contrasted with phyletic (that is, evolutionary) gradualism. Of course, the term *rapid* in this context is relative, since we are talking about vast spans of time. Life on Earth has existed for about 3,000 million years, and the fossil record goes back some 1,000 million years. This is the case, in part, because to leave fossilized remains, an organism must have "hard parts" that can become mineralized to turn into fossils. (See Paleontology for more on these subjects.)

REAL-LIFE APPLICATIONS

The Diversity of Mammals

One of the most interesting examples of speciation is that which has produced the vast array of species, including humans, that fall within the mammalian class. Mammals began evolving before the dawn of the Cenozoic era about 65 million years ago. The Cenozoic era, which started with a catastrophic event that brought about the mass extinction of the dinosaurs and

the end of the Mesozoic era (see Paleontology), is truly the age of the mammal. Just as dinosaurs dominated the Mesozoic, today the world belongs to mammals as to no other class of creature.

Since its humble beginnings in the shadow of the dinosaurs, class Mammalia has undergone a massive radiation to the point that today some 4,625 species of mammal, in about 125 families and 24 orders, are recognized. (That number is changing, as noted later in the context of elephants.) This diversity is tied closely to mammals' enormous mobility, which facilitated their spread throughout the world. Aside from much less complex life-forms, such as arachnids and insects (see Parasites and Parasitology), mammals are believed to be distributed more widely throughout the world than any other comparable taxonomic grouping. Insects may be the most diverse of all animal classes, with numbers of species that may be many times greater than the number of mammals, but considering mammals' much-greater level of physical development and complexity, the diversity of their species is astounding.

MAMMALS' EARLY EVOLUTION. In the next section we list the orders of mammals and give very brief descriptions of each. The purpose here is not to provide anything like a comprehensive discussion but rather to illustrate the enormous range of species in a class that includes anteaters, dolphins, humans, elephants, and bats. The fact that all these diverse creatures, and many more, emerged from a common evolutionary lineage is almost as amazing as the fact that this common ancestor was a reptile.

Mammals are believed to have come from the reptilian order Therapsida, which emerged during the Triassic period (from about 245 to 208 million years ago) in the early part of the Mesozoic era. Over the course of many millions of years, these creatures began to develop a number of mammal-like qualities—in particular, endothermy, or the ability to maintain internal temperature regardless of environmental conditions. In other words, these cold-blooded creatures became warm-blooded. This evolutionary process was as complex as it was lengthy. Nor was there a clean break with the past—no moment when the therapsids faded away or when it would have been clear that mammals had taken the place of their reptilian ancestors. Rather, in what must have been a fascinating taxonomic situation, for many millions of years, species that combined aspects of both reptiles and mammals walked the earth.

Mammalian Orders

The listing of the 20 orders of living mammals that follows is arranged not alphabetically but in the probable order in which these groups evolved. (This is not to imply that the process was orderly or linear; it was not.) Very few dates are given, simply because there is much dispute in most cases. Numbers of species within each order are also a subject of debate among taxonomists, and therefore these numbers are not always precise.

In the essay, Species, there is a taxonomic listing of the obligatory ranks for humans; included within that listing is a short description of the kingdom (Animalia), phylum (Chordata), and subphylum (Vertebrata) to which mammals belong. *Mammal* itself is defined as a vertebrate (an animal with a spinal column) that feeds its young from special milk-secreting glands, termed *mammae,* located on the mother's body. Mammals are warm-blooded or endothermic, meaning that their internal temperatures remain relatively stable, and their bodies usually are covered with hair. They have other distinguishing characteristics as well, such as a relatively large cranium (skull) with a hinged lower jaw attached to it.

MONOTREMES. Order Monotrema consists of primitive, egg-laying mammals spread throughout parts of the region known as Oceania, which includes Australia, New Zealand, and islands of the southeastern Pacific. The habitat of this order lies specifically in Australia, Tasmania, and New Guinea. Monotremes, as they are called, are distinguished further by the fact that their mammary glands are without nipples, that teeth are present only in the young, and that adults have horny beaks.

The monotremes illustrate the fact that to be constituted as an order or family, a taxon, or taxonomic group, need not have large numbers. The entire order consists of a single existing species, the duck-billed platypus, which constitutes a family of its own, and two species of echidnas, creatures that look like a cross between a platypus and a porcupine. (The "porcupine" look comes from the fact that their bodies are covered in spines, or spiky protrusions.)

MARSUPIALS. The marsupials, or order Marsupialia, include two other famous ani-

mal citizens of Oceania: the kangaroo and its close relative, the wallaby. Marsupials' young are poorly developed at birth and must continue to grow while attached to their mothers' nipples. For this reason, they must remain close to the mother, and therefore natural selection for marsupials favored those strains in which females possess a pouch bearing four teats.

Immediately after birth, the young marsupial (a kangaroo baby is called a joey) installs itself in the mother's pouch. Given this situation, marsupials can support only one offspring a year and thus are not given to the large litters that characterize another order, Carnivora, which we discuss later. Kangaroo offspring remain in the pouch until the age of about 7-10 months, by which time the mother has conceived again; the female kangaroo goes into heat just a few days after giving birth. The embryonic kangaroo remains in a state of dormancy, or arrested development, until the older sibling has left the pouch.

The marsupial order (some authorities call it a *superorder,* with numerous subordinate orders) consists of some 240 species. The greatest number of these, including many species of kangaroo, wallaby, wombat, and koala, are found exclusively in Australia. Some 70 additional species are scattered across parts of Oceania, including Australia, Tasmania, New Guinea, and smaller islands. There are an additional 70 species in the Americas, including four species of the genus *Didelphis*—the large American opossum, better known in the southern United States as possums.

Why the preponderance of marsupials in Australia and Oceania as a whole? The reason lies in Earth's geologic history, which has seen regular collisions and divisions of the continents, which are even today shifting slowly under our feet. It appears that prior to about 70 million years ago, at a time when most of Earth was united in a single supercontinent called Pangaea, marsupials originated in what is now North America and migrated to the land masses that became Australia and Oceania. Because the bulk of marsupial species remained on Australia and nearby areas when Pangaea began to break apart, marsupials underwent much greater speciation there than in North America.



MARSUPIALS' YOUNG ARE POORLY DEVELOPED AT BIRTH AND MUST CONTINUE TO GROW WHILE ATTACHED TO THEIR MOTHERS' NIPPLES. IMMEDIATELY AFTER BIRTH, THE YOUNG KANGAROO (CALLED A JOEY) INSTALLS ITSELF IN THE MOTHER'S POUCH AND REMAINS THERE UNTIL THE AGE OF 7-10 MONTHS. *(© Michael S. Yamashita/Corbis. Reproduced by permission.)*

XENARTHRANS, INSECTIVORES, SCANDENTIA, AND DERMOPTERA. Known variously as xenarthrans and edentates, members of order Xenarthra either lack teeth or have very small ones. Evolutionary development has adapted the forward limbs of these creatures for digging or for holding on to the branches of trees. Included in this order are some 30 species of sloth, anteater, and armadillo. Sloths are herbivores, armadillos are omnivores (i.e., they eat plants and small animals), and anteaters, as their name would suggest, are hard-core insectivores.

The term insectivore can refer to any organism that lives by eating insects, but it is also the name for members of the order Insectivora, which includes shrews, hedgehogs, moles, and various other, less well known groups. Some 400 species, of which about 300 are shrews in a single family (Soricidae), make up this order. Not only their diet but also their pointed snouts and rodent-like appearance distinguishes this group. Many, but not all, are diggers, like the xenarthrans. Like all mammals, they have the pentadactyl limb (an appendage with five digits,

like the human arm and hand)—in their case, a foot with five toes.

Order Scandentia, which is identical with the family Tupaiidae, or tree shrews, is sometimes grouped with order Insectivora. Despite their name, tree shrews, of which there are five genera and between 15 and 19 species, may live either on the ground or in the trees. Squirrel-like in appearance, they have strong claws on all their toes and are excellent climbers.

Another very small order of tree-dwellers is Dermoptera, which consists of just two species of flying lemur. Found in Indonesia and the Philippines, these creatures are equipped with skin flaps adapted for gliding. This aspect of their morphological makeup calls to mind the "flying" squirrel, but their nocturnal habits are more like those of lemurs (discussed later, with other primates); hence their common name.

CHIROPTERANS. Among the most fascinating of mammalian orders is Chiroptera, better known as bats. This order, which consists of about 900 species in some 175 genera, is the only group of truly flying mammals, as opposed to the "flying" lemurs we just discussed. Yet they, too, have the pentadactyl limb, only in their case the forelimb has been adapted as a wing. Among the intriguing features of bats is their use of acoustic orientation, or echolocation, to find their way through the dark caves and nocturnal exteriors that make up their world. Contrary to popular belief, they are not blind, but they do have very small eyes, simply because vision is not important for bat navigation. (See Migration and Navigation for more about this subject.)

As befits an order with such a wide array of species, bats run the gamut with respect to their eating habits. The majority of bat species are insectivores that consume many thousands times their weight in insects each year. Many others are fruit bats, important members of the ecosystems they occupy, because they consume fruit and spread seeds, helping assist in seed dispersal. (Some bats also aid in pollination; see Reproduction). Then there are the three species of vampire bat, which are largely responsible for bats' unfortunate reputation with humans.

Members of subfamily *Desmodontinae,* species of vampire bat include *Diaemus youngi* and *Diphylla ecaudata.* However, the best-known variety is the common vampire bat, *Desmodus rotundus,* which is native to an area that stretches from the southwestern United States to the northwestern third of South America. As one would suspect of a creature named vampire, they live off blood, which they suck at night from birds or other mammals, including humans. These creatures are livestock pests and strike fear in humans both because of the imaginary association with vampires and for the quite real threat of contracting rabies from them. The vast majority of bats, however, are creatures that cause no harm to humans and often are unfairly persecuted as the result of human prejudices. Even in the case of the vampire bat, there is a strong possibility that it may one day help save human lives. Scientists have discovered that the saliva of *Desmodus rotundus* is better than any other known substance for keeping blood from clotting; therefore, vampire bat saliva may one day be adapted for use in treating heart attacks and strokes.

PRIMATES. The order of humans, Primates, falls approximately in the middle of the mammalian class in terms of evolutionary order. This is an interesting aspect of speciation, evolution, and taxonomy: even though humans themselves are the most advanced of all creatures, it is not a logical necessity that we should come from the most recently evolved order. In fact, the opposite would seem to be the case. To produce a species whose intelligence dwarfs that of all other animals, the line of descent should be a long one. Where primates are concerned, that is certainly the case. The oldest primate samples date back some 75 million years, or long before the end of the Mesozoic.

Because it is from primates that humans draw their lineage, more has been written about primate evolution than on that of all other mammalian orders combined. The subject is such a vast one that we will not attempt to approach it here, except to encourage the reader to study in more detail elsewhere the process by which the human lineage emerged from order Primates, family Hominidae, and genus *Homo.*

Primates consist of two broad groups, suborders Prosimii and Anthropoidea. The first, the prosimians, includes five families (or six, since tree shrews are sometimes included) of lemurs, lorises, and tarsiers. The other suborder, known as the *higher* primates, encompasses another six families: marmosets and tamarins; South American monkeys other than marmosets; African and Asian monkeys; lesser apes, or siamangs and gibbons; great apes, or orangutans, gorillas, and

chimpanzees; and humans, both living and extinct. (Most orders contain extinct members, but for the most part they are not discussed here.)

Most primates are tree dwellers, and among the approximately 230 species, there is enormous variation in eating habits. Many lemurs are insectivores, while great apes tend to be fruit eaters. Quite a few are omnivores, though no primate other than humans is known for eating large mammals, such as cows, sheep, and pigs. The pentadactyl limb (an appendage with five digits) is a significant feature for primates, which alone have the advantage of the opposable thumb for grasping. Humans and a few other primate species are also the only animals with four limbs who are not only capable of standing upright but also function best in this way.

CARNIVORES. As with insectivore, *carnivore* is a name both for an eating preference—in this case, meat—and for members of a primate order, Carnivora. Most members of this extraordinarily varied group eat meat, including, in some cases, the "meat" of insects. Bears and some other species are omnivorous, meaning that they also eat plants, and hyenas and jackals are classic examples of detritivores, or animals who feed on the remains of other creatures.

The distinction between detritivore and carnivore relates not to the materials each consumes but to their place in the food web. Rather than consume live creatures, hyenas and jackals feed on the carcasses of dead ones. Usually these creatures are artiodactyls (discussed later), such as antelopes, which have been killed by other carnivores—big cats, such as the lion or cheetah. After the big cats have fed on the fleshy parts of the prey, hyenas come to consume the flesh that remains, and they are followed by jackals and vultures, swoop in to pick the bones. These detritivores help process the remains of formerly living things, which ultimately return to the soil. (See Food Webs for more on this subject.)

Clearly, all members of order Carnivora eat meat, though in different ways and sometimes in combination with fruit or other vegetation. Natural selection has equipped them for this purpose with sharp claws and teeth. Carnivora includes some 270 species grouped into ten families, listed here:

- Canidae (dogs, wolves, jackals, and foxes)
- Felidae (cats)
- Hyaenidae (hyenas)
- Mustelidae (skunks, mink, weasels, badgers, and otters)
- Otariidae (eared seals)
- Odobenidae (walrus)
- Phocidae (earless seals)
- Procyonidae (raccoons)
- Ursidae (bears)
- Viverridae (mongooses and civets).

Note that Felidae is a particularly varied family of some 36 species: lions, lynxes, tigers, leopards, and even ordinary domesticated cats. Thirty-five species belong to a single subfamily, Felinae, which is native to most parts of the world other than Australia, Madagascar, most oceanic islands, and, of course, Antarctica. The last species, the cheetah (*Acinonyx jubatus*), is segregated into another subfamily, Acinonychinae, primarily because this cat, native to Africa and southwest Asia, is a daytime hunter, unlike its nocturnal cousins.

CETACEANS AND SIRENIANS. Orders Cetacea and Sirenia include the majority of aquatic mammals, as opposed to the many amphibious mammals, such as seals, sea lions, sea elephants, and walruses, that belong variously to families Otariidae, Odobenidae, and Phocidae of the order Carnivora. Cetaceans include whales, dolphins, and porpoises, while sirenians are made up of just three species of manatee and one of dugong. Sirenians are large, friendly creatures that inhabit the Atlantic coast and tributary rivers (manatee) or the Indian and Pacific coastlines (dugong), but cetaceans are much more familiar.

With cetaceans, two questions, one specific and one general, often arise. The answer to the first of these, "What is the difference between a dolphin and a porpoise?," is that a porpoise is smaller and more chubby and has a blunt snout, whereas a dolphin has a beaklike snout. Some taxonomists and marine biologists put porpoises in the same family as dolphins, whereas others treat them as two different families. The more general, and much more important, question is "Why are these mammals living in the water?" In fact, life itself first appeared in the sea, so perhaps the question should be "Why or how did anything start living on land?" The transition from water to land took place long before the age of the dinosaurs, much less the emergence of mam-

mals, but later, some mammals began to return to the water, probably about 70 million years ago.

Certainly, there is no question that cetaceans are mammals, a fact first recognized by Aristotle (384–322 B.C.), a Greek thinker who is noted not only as one of the greatest philosophers of all time but also as the father of the biological sciences. (See Taxonomy for more about Aristotle's contributions.) As Aristotle observed, whales and dolphins bear live young and suckle them with milk-producing glands; their bodies have hair, albeit only very small strands; and they possess lungs, breathing air through a blowhole.

As evidence of their terrestrial, or land-based, origins, consider that a whale fetus possesses the remnants of four limbs, each with five fingers (the pentadactyl limb), like any land mammal. Adult whales and dolphins have the streamlined, fishlike morphological appearance that is necessary for life underwater, but their resemblance to fishes is of the superficial, analogous variety discussed in Taxonomy. They have maintained and modified key terrestrial features; for example, a blowhole atop the head—one in dolphins, two in whales—replaces the nostrils, and thus the passageways for food and air are completely separate. This differs from the situation with most terrestrial mammals, which take in food and air through the same opening.

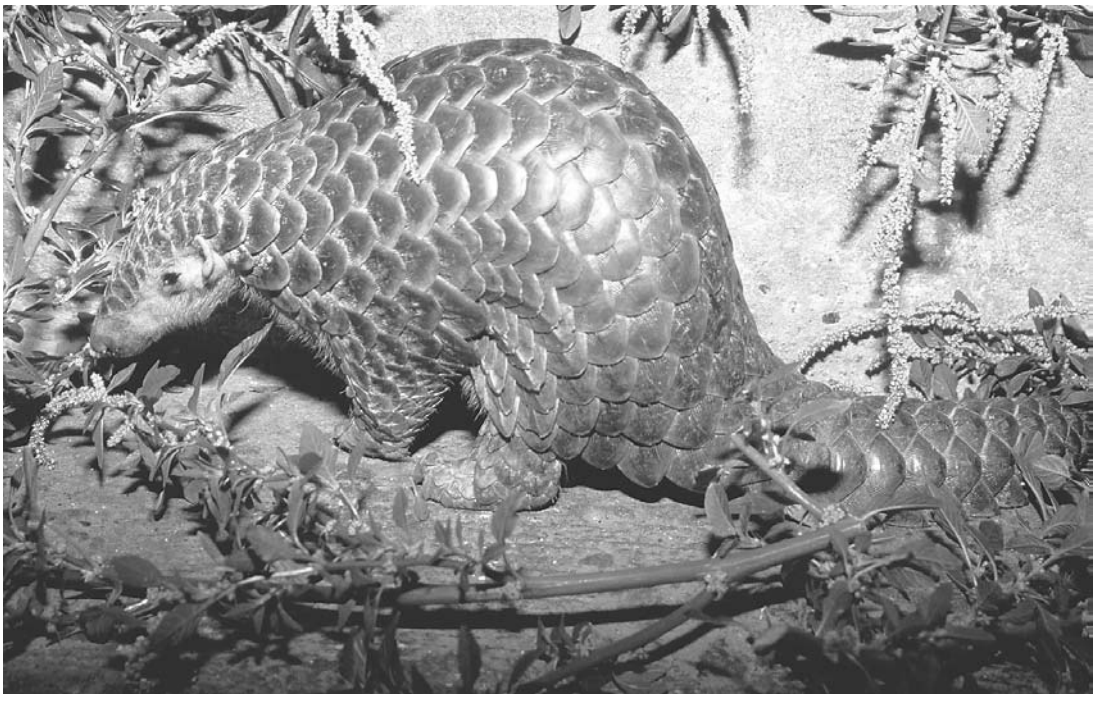
PROBOSCIDEANS, PERISSODACTYLS, AND HYRAXES. Moving from the largest aquatic mammals, the whales, to the largest terrestrial variety, we come to the order Proboscidea, which includes elephants. Our discussions of most orders in class Mammalia have illustrated particular aspects of taxonomy and speciation, and so it is with proboscideans, which give evidence of the many species from the past that are gone forever. The order is a large one, with three suborders and some 300 species, but anyone who searches for most of those species will search in vain. All but three species are extinct. These three are the Asian elephant (*Elephas maximus*) and two varieties of African elephant (*Loxodonta africana* or African savanna elephant and *Loxodonta cyclotisare,* the African forest elephant). Until 2001, taxonomists believed that there were only two living species of elephant. (See Taxonomy for more on this subject.)

Another 16 species belong to the order Perissodactyla, herbivores whose hind feet bear either one or three hoofed toes. Included among perissodactyls is another large animal from the grasslands of Africa and tropical Asia: the rhinoceros. The group also encompasses donkeys, zebras, and tapirs, but by far the most important in human terms is *Equus caballus,* the domesticated horse. Described by the French zoologist Comte Georges de Buffon (1707–1788) as "the proudest conquest of man," the horse was domesticated (adapted so as to be useful and advantageous for humans) some 6,000 years ago. Nonetheless, feral or wild horses remain an important subspecies.

Order Hyracoidea also consists of hoofed mammals: seven species of hyrax, a primarily herbivorous creature native to Africa and the far southwestern extremities of Asia. Hyraxes are sometimes lumped in with pikas under the term rock rabbit, but, in fact, pikas are lagomorphs, a group we discuss later. To further the confusion, hyraxes are probably the animal called a coney in the Bible, even though there is an animal called a *cony* (no "e") that is actually a lagomorph. This is just one of many examples of confusion resulting from the complexities of the animal world and humans' attempts to name and classify its members.

TUBULIDENTATES. For most orders, the lowercase adjectival name (e.g., primates, carnivores, insectivores, and so on) is commonly used. On the other hand, the names hyracoidean and tubulidentate are seldom used for more obscure groups, such as Hyracoidea and Tubulidentata. If any order of mammal is obscure, it is Tubulidentata, which emerged some 60 million years ago and which consists of a single species: the African ant bear (*Orycteropus afer*). The latter creature is better known by the name *aardvark,* which in the Afrikaans language means "earth pig."

Aardvarks at first glance might seem to belong with anteaters, sloths, and armadillos in the order Edentata, and that is what taxonomists thought for a long time. The latter half of the name tubulidentate, however, suggests the area of differentiation: the teeth. Aardvarks' teeth are unique among those of all mammals. Viewed from the top, the aardvark's jawbone is V-shaped, with the teeth midway along either side of the *V.* The teeth themselves are not fixed to the jaw but rest in the flesh attached to it, and instead of being covered with enamel, they are protected with a cementlike substance. The substance comes from tubules that run under the teeth.



ORDER PHOLIDOTA CONSISTS OF SEVEN SPECIES OF SCALY ANTEATER, OR PANGOLIN. THE WORD PANGOLIN COMES FROM A MALAY TERM MEANING "ROLLING OVER," A REFERENCE TO THE FACT THAT WHEN IT IS THREATENED, THE ANIMAL CURLS INTO A LITTLE BALL. *(© Keren Su/Corbis. Reproduced by permission.)*

ARTIODACTYLS. Like many other mammalian orders we have discussed, members of order Artiodactyla are ungulates, or hoofed animals. Whereas perissodactyls have odd-numbered toes, artiodactyls have even-numbered toes—either two or four—on each foot. This large group, consisting of some 220 species, comprises a wide variety of well-known species in nine families. Among them are cows, pigs, sheep, goats, deer, antelope, bison, camels, giraffes, hippopotamuses, and numerous less well known varieties, such as okapi, pronghorn, peccaries, and deerlike chevrotains.

The camel family is particularly widespread geographically, including as it does many varieties—the llama, alpaca, and vicuña of South America—whose home is far from the habitats in the Near East that are associated with the camel. In this family is what may be a previously undiscovered species, whose existence the British Broadcasting Corporation (BBC) reported in early 2001. Living on a former nuclear weapons testing range in a remote region of Chinese central Asia, these creatures drink saltwater, which in itself is an unusual characteristic.

Although it is extraordinarily hardy, even by the standards of camels, the central Asian camels are threatened; fewer than 1,000 remain. As the BBC reported, this makes them more endangered than the more well known giant panda. The creatures survived nuclear testing in the area, which ceased in 1996, but they continue to be threatened by much less spectacular varieties of explosive: dynamite and land mines, planted by hungry locals. John Hare of the Wild Camel Protection Foundation told the BBC, "We found land mines put by the saltwater springs. So when the camels come to drink, they step on them. Bang! They are blown to pieces and picked up as meat."

As to whether the camels constitute a separate species, the molecular geneticist Olivier Hanotte told the BBC: "There are two possibilities here. One is that the domestic camel was bred from these wild ones some time back in history. The second is that the domestic camel we see today was bred from another species that has disappeared. This would mean that these wild camels are a totally separate species." As of early 2002 the camels' fate, both practically and taxonomically, remained undecided.

PHOLIDOTA/PANGOLINS. Order Pholidota consists of seven species of scaly anteater, or pangolin. Members of this order are normally called *pangolins,* rather than an adjecti-

KEY TERMS

ADAPTIVE RADIATION: A diversification of species over time as a result of specialized adaptations by particular populations of organisms.

ALLOPATRIC SPECIATION: A type of speciation that occurs when a population of organisms is divided by a geographic barrier.

ANALOGOUS FEATURES: Morphologic characteristics of two or more taxa that are superficially similar but not as a result of any common evolutionary origin.

CARNIVORE: A meat-eating organism, or an organism that eats *only* meat (as distinguished from an *omnivore*).

CLASS: The third most general of the obligatory taxonomic classification ranks, after *phylum* but before *order.*

DETRITIVORES: Organisms that feed on waste matter, breaking organic material down into inorganic substances that then can become available to the biosphere in the form of nutrients for plants. Their function is similar to that of decomposers; however, unlike decomposers—which tend to be bacteria or fungi—detritivores are relatively complex organisms, such as earthworms or maggots.

DNA: Deoxyribonucleic acid, a molecule in all cells, and many viruses, containing genetic codes for inheritance.

DOMESTICATE: To adapt an organism, whether plant or animal, so as to be useful and advantageous for humans.

FAMILY: The third most specific of the seven obligatory ranks in taxonomy, after *order* but before *genus.*

GENE: A unit of information about a particular heritable (capable of being inherited) trait that is passed from parent to offspring, stored in DNA molecules called *chromosomes.*

GENE POOL: The sum of all the genes shared by a population, such as that of a species.

GENUS: The second most specific of the obligatory ranks in taxonomy, after *family* but before *species.*

HERBIVORE: A plant-eating organism.

HYBRID: The product of sexual union between members of two species or other smaller and less genetically separate groups, such as two races. In the case of species hybrids, the process of hybridization involves genetic abnormalities that lead in most cases to sterility.

INSECTIVORE: An insect-eating organism.

KINGDOM: The highest or most general ranking in the obligatory taxonomic system. In the system used in this book there are five kingdoms: Monera, Protista, Fungi, Plantae, and Animalia.

val form of Pholidota. The word *pangolin* comes from a Malay term meaning "rolling over," a reference to the fact that when it is threatened, the animal curls into a little ball. As with the aardvark, members of this order once were grouped with Edentata but now are considered a separate order. Pangolins are also like aardvarks in the sense that their evolutionary relationship to other mammals is not clear.

RODENTS, LAGOMORPHS, AND MACROSCELIDEANS. Rodents, or mem-

KEY TERMS CONTINUED

MORPHOLOGY: Structure or form, or the study thereof.

MUTATION: Alteration in the physical structure of an organism's DNA, resulting in a genetic change that can be inherited.

NATURAL SELECTION: The process whereby some organisms thrive and others perish, depending on their degree of adaptation to a particular environment.

NUMERICAL TAXONOMY: An approach to taxonomy in which specific morphological characteristics of an organism are measured and assigned numerical value, so that similarities between two types of organism can be compared mathematically by means of an algorithm. Numerical taxonomy also is called *phenetics.*

OMNIVORE: An organism that eats both plants and other animals.

ORDER: The middle of the seven obligatory ranks in taxonomy, more specific than *class* but more general than *family.*

PENTADACTYL LIMB: An appendage with five digits, like the human arm and hand. This appendage is common to all mammals, though it may take very different forms—for example, the dolphin's flipper.

PHENETICS: Another name for *numerical taxonomy.*

PHYLOGENY: The evolutionary history of organisms, particularly as that history refers to the relationships between lifeforms, and the broad lines of descent that unite them.

PHYLUM: The second most general of the obligatory taxonomic classification ranks, after *kingdom* and before *class.*

SPECIATION: The divergence of evolutionary lineages and creation of new species. See *allopatric speciation* and *sympatric speciation.*

SPECIES: The most specific of the seven obligatory ranks in taxonomy. Species often are defined as a population of individual organisms capable of mating with one another and producing fertile offspring in a natural setting. Also, members of the same species share a gene pool.

SYMPATRIC SPECIATION: A type of speciation that occurs when a group of individuals becomes reproductively isolated from the larger population of the original species. This type of speciation typically results from mutation.

TAXON: A taxonomic group or entity.

TAXONOMY: The area of the biological sciences devoted to the identification, nomenclature, and classification of organisms according to apparent common characteristics.

VERTEBRATE: An animal with a spinal column.

bers of order Rodentia, are familiar to us as both pests and pets as well as aids to research through their use as test subjects in laboratories. They are also the most abundant of all mammalian orders: about one-fourth of all families, 35% of all genera, and 50% of all living species of mammal are rodents. The group consists of some 2,205 species, among them mice, rats, squirrels, beavers, gophers, and porcupines. The name *rodent* comes from the Latin *rodere,* meaning "to gnaw," and, indeed, the defining characteristic of rodents is their chisel-like upper front teeth.

Whereas rats typically are despised creatures, mice (distinguished from rats simply because they are smaller) often are considered cute—that is, if the mouse in question is a pet or a laboratory mouse, rather than a pest chewing up the insulation or electrical wiring in someone's house. The fact that rodents are so often pests and pets arises in part from rodents' close association with humans. This is a distinction in itself, since few mammal orders manage to live successfully in such close proximity to humans. Not only do squirrels often live around human dwellings, but other species (for better or worse) often enter structures where humans live or work. Particularly notorious in this regard are black rats (*Rattus rattus*) and Norway rats (*R. norvegicus*), which are just two of some 500 rat species.

The two remaining orders of mammal also are composed of small, furry creatures. Lagomorphs, or members of the order Lagomorpha, are small mammals with large upper incisors (front teeth) but no canines or eyeteeth and with molars that lack roots. The 80-odd species of lagomorphs include rabbits, hares, and their lesser-known cousin the pika, or mouse-hare. The difference between rabbits and hares relates to their conditions at birth: rabbits are furless, blind, and helpless, whereas hares are furry, have open eyes, and are capable of hopping within minutes.

Finally, 28 species of elephant shrew, or jumping shrew, make up the order Macroscelidea, a collection of species known for their long, flexible, sensitive snouts. Some authorities group macroscelideans with order Insectivora, whereas others place them in another order, Mentophyla, with tree shrews. The latter often have been placed variously in orders Scandentia, Insectivora, or Primates, indicating that many areas of mammalian taxonomy remain in dispute.

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DISEASE

DISEASE
NONINFECTIOUS DISEASES
INFECTIOUS DISEASES

DISEASE

CONCEPT

Disease is a term for any condition that impairs the normal functioning of an organism or body. Although plants and animals also contract diseases, by far the most significant disease-related areas of interest are those conditions that afflict human beings. They can be divided into three categories: intrinsic, or coming from within the body; extrinsic, or emerging from outside it; and of unknown origin. Until the twentieth century brought changes in the living standards and health care of industrialized societies, extrinsic diseases were the greater threat; today, however, diseases of intrinsic origin are much more familiar. Among them are stress-related diseases, autoimmune disorders, cancers, hereditary diseases, glandular conditions, and conditions resulting from malnutrition. There are also illnesses, such as Alzheimer's disease, whose causes remain essentially unknown.

HOW IT WORKS

Classifying Diseases

Any condition that impairs the normal functioning of an organism can be called a disease. In the human organism, as in all others, there are certain basic requirements, which in the human body include the need for a certain proper amount of oxygen, acidity, salinity (salt content), nutrients, and so on. These conditions must all be maintained within a very narrow range, and any deviation can bring about disease.

Diseases can be classified into three general groups. There are conditions that are infectious, or extrinsic, meaning that they are caused by an infection through which a virus, bacterium, or other parasite enters the body. Infectious diseases, infections, and the immune system that usually protects us against them are discussed elsewhere in this book. Our attention in the present context will be devoted to the other two broad categories—noninfectious, or intrinsic, diseases and diseases of unknown origin.

CLASSIFYING INTRINSIC DISEASES. There are several basic varieties of intrinsic disease, or conditions that are neither contagious nor communicable. These varieties are listed in the next few paragraphs. The essay Noninfectious Diseases includes a discussion of other systems for classifying diseases of either the intrinsic or the extrinsic variety.

Hereditary diseases: diseases that are genetic, meaning that they are passed down from generation to generation. An example, discussed in Noninfectious Diseases, is hemophilia. Heredity is not a "cause," and some of the diseases of unknown origin may be transmitted from parent to offspring. Some forms of cancer are hereditary as well, as are other conditions discussed elsewhere in this book. (See Nonifectious Diseases, Mutation, and Heredity.)

Glandular diseases: Conditions involving a gland—that is, a cell or group of cells that filters material from the blood, processes that material, and secretes it either for use again in the body or to be eliminated as waste. Examples include diabetes mellitus, examined in Noninfectious Diseases, as well as various kidney and liver diseases, among them, hepatitis and jaundice. Goiter, a swelling in the neck area caused by a diet poor in iodine, is both a glandular and a dietary condi-

tion, a fact that illustrates the overlap between disease types.

Dietary diseases: These are all illnesses that relate to nutrient deficiencies—either an overall lack of adequate nutrition (i.e., malnutrition) or the absence of a key nutrient. Examples include pellagra, scurvy, and rickets, all of which are vitamin deficiencies, as well as kwashiorkor, which brings about a swollen belly and is caused by a lack of protein. Vitamin deficiencies are discussed in Vitamins, and kwashiorkor and other varieties of malnutrition are examined in Nutrients and Nutrition.

Cancers: Cancer is not just one disease but some 100 conditions. Its two main characteristics are uncontrolled growth of diseased cells in the human body and migration of the disease from the original site to distant sites within the body. If the spread is not controlled, cancer can result in death. (See Noninfectious Diseases for more.)

Stress-related diseases: Some heart conditions are hereditary or glandular, but quite a few diseases of the heart and circulatory system are exacerbated by stress. Examples include heart murmurs, hardening of the arteries, and varicose veins. We will examine heart disease and the general effects of stress shortly.

Autoimmune diseases: This is a particularly terrifying category of disease, because it involves a rejection of the body itself by the body's own immune system. Autoimmune diseases, examples of which include lupus and rheumatoid arthritis, are discussed in The Immune System.

DISEASES OF UNKNOWN ORIGIN. Finally, there are diseases for which there is no known cause. In some cases, it is possible that heredity, diet, or some other aspect of human existence has a role, but it is not certain. And even if, say, heredity plays a part, the exact hereditary factors are not established. In any case, many of the categories of disease we have listed do not amount to "causes," but rather are types of disease. Moreover, some diseases classifiable in one of the listed categories also belong in the ranks of the diseases with unknown causes. For instance, many autoimmune diseases are mysterious to scientists. Likewise, chronic fatigue syndrome, considered a disease of unknown origin, is obviously a stress-related disorder, while fibromyalgia, characterized by sore muscles and tissues, may be stress-related as well. Two brain diseases of unknown origin, Creutzfeldt-Jakob and Alzheimer's disease, are discussed near the conclusion of this essay.

REAL-LIFE APPLICATIONS

A Changing Threat

At one time the diseases that posed the greatest threat to human survival were infectious ones, such as the Black Death (actually a combination of bubonic and pneumonic plague), which killed about a third of Europe's population during the period from 1347 to 1351. Plagues or epidemics, in fact, are among the persistent themes in history, punctuating the fall of empires and the rise of others.

A plague that struck the eastern Roman (Byzantine) Empire in the sixth century, for instance, brought an end to a plan by the great Justinian I to reconquer the Italian peninsula and restore Roman rule in western Europe. It also spelled the beginning of the end of Byzantine glory (though the empire hung on until 1453) and opened the way for the rise of Islam and Muslim influence over the Mediterranean. Thus, the course of history up to the present day, including the events of the European Middle Ages, the Crusades, and even the modern-day conflict between the West and Islamic terrorists, can be traced in part back to a plague in about A.D. 540.

Wherever people have gathered in large numbers, infectious diseases have arisen. Smallpox and chicken pox, cholera and malaria, diphtheria and scarlet fever, influenza and polio—these and many other diseases have threatened the very survival of whole populations, bringing about a collective death toll that dwarfs that of twentieth-century wars and genocide. Yet it was in the twentieth century—ironically, the era when humans discovered the capacity to kill themselves in truly frightening numbers through world wars, nuclear weaponry, and totalitarian social experiments—that the threat of infectious diseases began to recede.

Thanks to successful vaccination programs, many infectious diseases are largely a thing of the past. This is true even of smallpox, a scourge that effectively ended in 1978 thanks to a United Nations inoculation program, but which reemerged as a potential threat of biological ter-



Illustration from the fifteenth-century Toggenberg Bible of people afflicted with bubonic plague. At one time such infectious diseases posed the greatest threat to human survival; in fact, plagues and epidemics are among the persistent themes in history, punctuating the fall of empires and the rise of others. *(© Bettmann/Corbis. Reproduced by permission.)*

rorism in the hands of political terrorists, such as the Islamic terrorist Osama bin Laden. It would be difficult for bin Laden's al-Qaeda organization to acquire samples of the virus, however; they are stored in only four or five laboratories worldwide (kept there for the purpose of making more vaccine if needed) and remain under heavy guard.

THE RISE OF INTRINSIC DISEASES. Rather than infectious diseases, the much greater threat today is in the form of intrinsic diseases, or ones that are neither communicable nor contagious. The leading causes of death in the United States are as follows:

- Heart disease
- Cancer
- Stroke
- Chronic obstructive lung diseases (e.g., emphysema)
- Accidents (motor vehicle or other)
- Pneumonia and influenza
- Diabetes mellitus
- Suicide
- Kidney disease
- Chronic liver disease and cirrhosis

Note that the one item on the list that is not an intrinsic disease and is not disease-related at all: accidents. After that is the first extrinsic disease entry on the list, number 6, pneumonia and the closely related condition influenza. Number 8, of course, is not related to disease—at least not physical disease. The high incidence of suicide, with 11.1 such deaths per 100,000 population, probably reflects the fact that the United States is an industrialized, wealthy nation. Ironically, people who are eking out a living, struggling for survival, are far less likely to end it all voluntarily.

Also reflective of America's high level of development is the overwhelming preponderance of intrinsic, noninfectious diseases on the list. Unquestionably, the greatest threat to human health today takes the form of noninfectious diseases, such as heart disease, cancer, and diseases of the circulatory system. This is true only in the industrialized world, however: whereas only about 25% of all patients who visit doctors in the United States do so because of infectious diseases, more than two-thirds of all deaths worldwide are caused by infectious diseases, such as malaria.

Stress and Heart Disease

Stress, simply put, is a condition of mental or physical tension brought about by internal or external pressures. Many events can cause stress: something as simple as taking a test or driving through rush-hour traffic or as traumatic as the death of a loved one or contracting a serious illness. Stress may be short-lived, as when facing a particular deadline, or it may be the ongoing, crippling stress related to a job that is slowly killing the victim.

People who experience severe traumas, such as soldiers in combat, may experience a condition called post-traumatic stress disorder (PTSD). This condition first came to public attention after World War I, a war that completely dwarfed all preceding conflicts in its intensity and brutality. Formerly bright-eyed, optimistic youths came home behaving like madmen or nervous wrecks, and soon the condition gained the nickname *shell shock*. (Actually, shell shock dated back more than 50 years, to what might be regarded as the first modern war in the West—the first "total war" involving relatively sophisticated weaponry and a fully engaged citizenry: America's Civil War, from which combatants returned home with a condition known as "soldier's heart.")

effects of stress. Whereas PTSD has a distinct psychological dimension, in many stress-related diseases there is not as obvious a link between mental states and bodily disorders. Nonetheless, it is clear that stress kills. Some of the physical signs of stress are a dry mouth and throat, headaches, indigestion, tremors, muscle tics, insomnia, and a tightness of the muscles in the shoulders, neck, and back. Emotional signs of stress include tension, anxiety, and depression. During stress, heart rate quickens, blood pressure increases, and the body releases the hormone adrenaline, which speeds up the body's metabolism. Stress may disrupt homeostasis, an internal bodily system of checks and balances, leading to a weakening of immunity.

Diseases and conditions associated with stress include adult-onset diabetes (see Noninfectious Diseases), ulcers, high blood pressure, asthma, migraine headaches, cancer, and even the common cold. The last, of course, is an infectious illness, but because stress impairs the immune system, it can leave a person highly susceptible to infection. Furthermore, medical researchers have determined that long-term stress causes the accumulation of fat, starch, calcium, and other substances in the linings of the blood vessels. This condition ultimately results in heart disease.

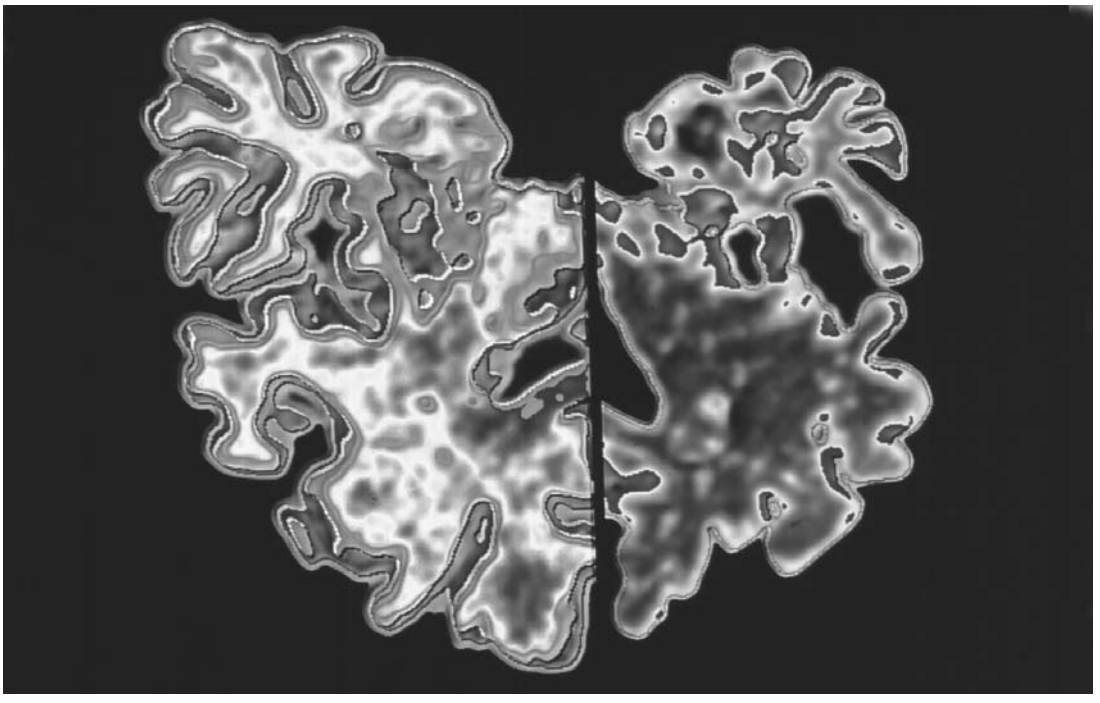
heart diseases. The human heart weighs just 10.5 oz. (300 g), but it contracts more than 100,000 times a day to drive blood through about 60,000 mi. (96,000 km) of vessels. An average heart will pump about 1,800 gal. (6,800 l) of blood each day. With exercise, that amount may increase as much as six times. In an average lifetime the heart will pump about 100 million gal. (380 million l) of blood. The heart is divided into four chambers: the two upper atria and the two lower ventricles. The wall that divides the right and left sides of the heart is the septum. Movement of blood between chambers and in and out of the heart is controlled by valves that allow transit in only one direction.

Given its importance to human life, it follows that heart disease is an extremely serious condition. Among the many illnesses that fall under the general heading of heart disease is congenital heart disease, a term for any defect in the heart that is present at birth. About one of every 100 infants is born with some sort of heart abnormality, the most common form being the atrial septal defect, in which an opening in the septum allows blood from the right and left atria to mix.

Coronary heart disease, also known as coronary artery disease, is the most common form of heart disease. A condition termed arteriosclerosis, in which there is a thickening of the artery walls, or a variety of arteriosclerosis known as atherosclerosis results when fatty material, such as cholesterol, accumulates on an artery wall. This forms plaque, which obstructs blood flow. When the obstruction occurs in one of the main arteries leading to the heart, the heart does not receive enough blood and oxygen, and its muscle cells begin to die.

Creutzfeldt-Jakob Disease

A particularly frightening category of unexplained diseases includes those that attack and destroy the brain. Among them are two conditions named after German scientists: the psychiatrists Alfons Maria Jakob (1884–1931) and Hans Gerhard Creutzfeldt (1885–1964) and the neurologist Alois Alzheimer (1864–1915). Creutzfeldt-Jakob dis-



Computer graphic of the brain of an Alzheimer patient (left) compared with a normal brain (right). Alzheimer's disease shrinks the brain, which shows signs of the degeneration of nerve cells, tangled protein filaments, and lesions caused by accumulation of beta-amyloid protein. *(Photograph by Alfred Pasieka. Photo Researchers, Inc. Reproduced by permission.)*

ease, fortunately, is a rare condition. The disease, first described by the two doctors in the 1920s, initially shows itself with the loss of memory, and within a few weeks it progresses to visual problems, loss of coordination, and seizure-like muscular jerking. Death usually follows within a year.

It appears that Creutzfeldt-Jakob disease ensues when a certain protein in the brain, known as prion protein, changes into an abnormal form. As to what causes that change, scientists remain in the dark. The disease attacks about one of a million people worldwide, and victims are typically about 50-75 years of age. During the 1990s something strange happened: the disease began affecting relatively large numbers of young people in the United Kingdom. A 1996 report of British medical experts, however, linked the surge in Creutzfeldt-Jakob cases to what might be considered a dietary condition: bovine spongiform encephalopathy, or mad cow disease, contracted from eating cattle with a form of prion disease. The only way to contract such a condition, however, is by eating the brain or spinal cord of an affected cow, something that could only happen in the case of hamburger or sausage, in which one does not always know what one is getting. The cows themselves got the disease from eating feed tainted with by-products of other cows, and as a result of the outbreak, Great Britain issued wide-ranging controls prohibiting the production of feed containing any materials from cows. (These particular feed-production practices were never common in the United States.)

Alzheimer's Disease

Whereas Creutzfeldt-Jakob disease is a little-known condition, Alzheimer's disease is all too familiar to the families of the more than four million sufferers in America today. Note the reference to the families rather than the victims themselves: one of the most devastating aspects of Alzheimer's disease is the patient's progressive loss of contact with reality, such that a patient in an advanced stage does not even know that he or she has the disease. A progressive brain disease that brings about mental deterioration, Alzheimer's disease is signaled by symptoms that include increasingly poor memory, personality changes, and a loss of concentration and judgment. Although most victims are older 65 years, Alzheimer's is not a normal result of aging. Up until the 1970s people assumed that physical and mental decline were normal and unavoidable

KEY TERMS

DISEASE: A general term for any condition that impairs the normal functioning of an organism.

EXTRINSIC: A term for a disease that is communicable or contagious and comes from outside the body. Compare with *intrinsic.*

GLAND: A cell or group of cells that filters material from the blood, processes that material, and secretes it either for use again in the body or to be eliminated as waste.

INTRINSIC: A term for a disease that is not communicable or contagious and comes from inside the body. Compare with *extrinsic.*

features of old age and dismissed such cases of deterioration as "senility." Yet as early as 1906, Alzheimer himself discovered evidence that pointed in a different direction.

In that year Alzheimer was studying a 51-year-old woman whose personality and mental abilities were obviously deteriorating. She forgot things, became paranoid, acted strangely, and just over four years after he began working with her, she died. Following an autopsy, Alzheimer examined sections of her brain under a microscope and noted deposits of an unusual substance in her cerebral cortex—the outer, wrinkled layer of the brain, where many of the higher brain functions, such as memory, speech, and thought, originate. The substance Alzheimer saw under the microscope is now known to be a protein called beta-amyloid. About 75 years later scientists and physicians began to recognize a strong link between "senility" and the condition Alzheimer had identified. Since then, the public has become more aware of the disease, especially since Alzheimer's disease has stricken such well-known figures as the former president Ronald Reagan (1911–) and the actress Rita Hayworth (1918–1987).

THE IMPACT OF ALZHEIMER'S DISEASE. A slight decline in short-term memory (as opposed to long-term memories of childhood and the like) is typical even in healthy elderly adults, but the memory loss seen in Alzheimer's disease is much more severe. As years pass, memory loss becomes greater, and personality and behavioral changes occur. Later symptoms include disorientation, confusion, speech impairment, restlessness, irritability, and the inability to care for oneself. Although victims may remain physically healthy for years, the progressive decline of their mental faculties is ultimately fatal: eventually, the brain loses the ability to control basic physical functions, such as swallowing. Persons with Alzheimer's disease typically live between five and ten years after diagnosis, although improvements in health care in recent years have enabled some victims to survive for 15 years or even longer.

Improvements in health care also may help explain the fact that the numbers of Alzheimer victims are growing. Medical discoveries of the twentieth century served to prolong life greatly, such that there are far more people alive today who are 65 years of age or older than there were in 1900. More accurate reporting no doubt plays a part as well. Whereas about 2.5 million cases were reported throughout the 1970s, by the end of the twentieth century there were some four million living Alzheimer victims, and by the mid-twenty-first century that number is expected to climb to the range of 13 million if physicians do not find a cure. Meanwhile, Alzheimer's causes the deaths of more than 100,000 American adults each year and costs $80–90 billion annually in health-care expenses.

UNDERSTANDING ALZHEIMER. It is not a simple procedure to diagnose Alzheimer's disease, and despite all the medical progress since the time of Alois Alzheimer, the "best" method for determining whether someone has the condition is hardly a good one. The only possible physical procedure for definitively diagnosing Alzheimer's disease is to open the skull and remove a sample of brain tissue for microscopic examination. This is rarely done, of course, because brain surgery is far too drastic a procedure for simply obtaining a sample of tissue.

The immediate cause of Alzheimer's is the death of brain cells and a decrease in the connec-

tions between those cells that survive. But what causes *that?* Many scientists today believe that the presence of beta-amyloid protein is a cause in itself, while others maintain that the appearance of the protein is simply a response to some other, still unknown phenomenon. Researchers have found that a small percentage of Alzheimer cases apparently are induced by genetic mutations, but most cases result from unknown factors. Various risk factors have been identified, but they are not the same as causes; rather, a risk factor simply means that if a person has *x,* he or she is more likely to have *y.* Risk factors for Alzheimer's include exposure to toxins, head trauma (former president Reagan suffered a serious head injury before the onset of Alzheimer's disease), Down syndrome (a genetic disorder that causes mental retardation), age, and even gender (women are more likely than men to suffer from Alzheimer's disease).

Familial Alzheimer's disease, an inherited form, accounts for about 10% of cases. Approximately 100 families in the world are known to have rare genetic mutations that are linked with early onset of symptoms, and some of these families have an aggressive form of the disease in which symptoms appear before age 40. The remaining 90% of cases may be caused by various combinations of genetic and as yet undefined environmental factors.

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NONINFECTIOUS DISEASES

CONCEPT

In contrast to infectious, or extrinsic, diseases, noninfectious, or intrinsic, conditions are neither contagious nor communicable. They arise from inside the body as a result of hereditary conditions or other causes, such as dietary deficiencies. Although infectious forms historically have been the most life-threatening varieties of disease and remain so even today in much of the world, noninfectious disease is a far more serious concern in industrialized nations, such as the United States. Some categories of intrinsic diseases include stress-related, dietary, and autoimmune conditions as well as diseases of unknown origin. Additionally, there are several other categories we examine in this essay: hereditary diseases, such as hemophilia; glandular conditions, of which diabetes mellitus is a powerful example; and cancer, of which there are approximately 100 different varieties.

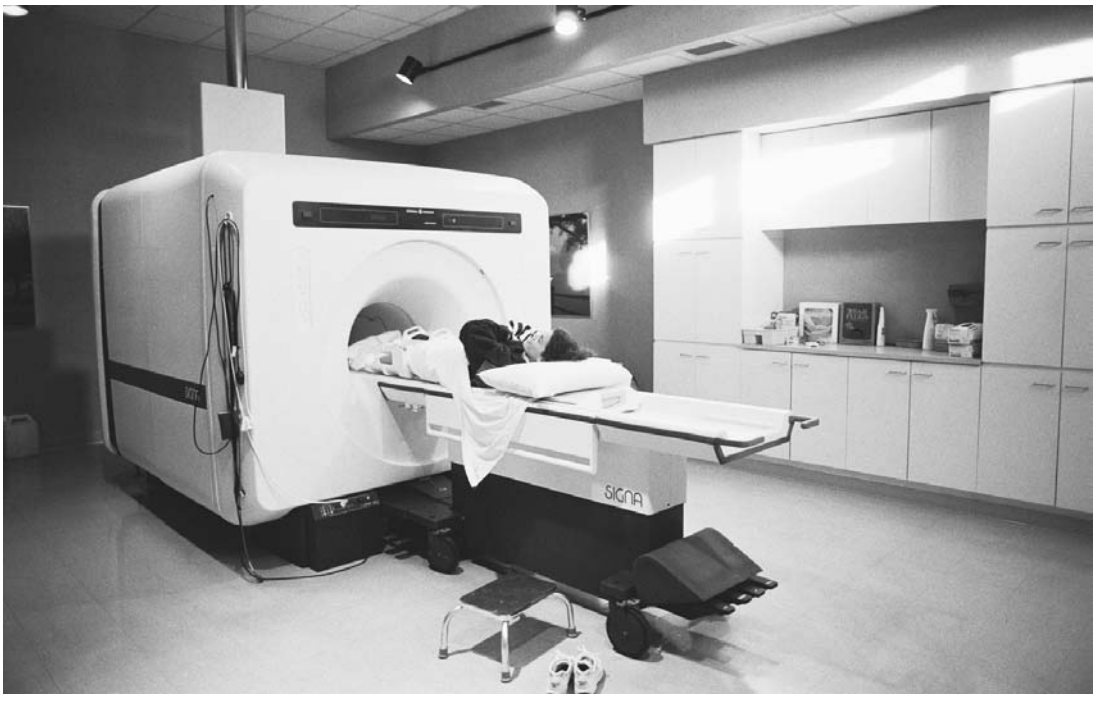
HOW IT WORKS

The Threat of Noninfectious Diseases

The world has long suffered under the threat of infectious diseases, some of which include smallpox, chicken pox, cholera, malaria, diphtheria, scarlet fever, influenza, polio, pneumonia, and even the common cold. Except for the last one, which is rarely fatal, such conditions have racked up a considerable death toll. For centuries people attributed these diseases to all manner of false causes, ranging from divine curses to an imbalance of bodily fluids. Only with the development of the microscope in the 1600s did scientists begin to identify the real cause behind most infectious diseases: bacteria, viruses, and other parasites. Infectious diseases, discussed elsewhere in this book (see Infection, Infectious Diseases, and Parasites and Parasitology), continue to pose a threat to life in underdeveloped nations. In North America, Europe, the emerging capitalist democracies of eastern Asia, and a handful of other materially and technologically advanced lands, however, infectious diseases have taken a back seat to noninfectious ones as well as to other threats.

CAUSES OF DEATH IN AMERICA. In the United States today, the four leading causes of death (see list in Disease) are noninfectious conditions: heart disease, cancer, stroke, and chronic obstructive lung diseases. The first of these conditions is discussed in Disease, and the second is examined later in this essay. Stroke, which occurs when a clot obstructs the flow of blood to the brain, may be classified along with heart disease as a stress-related ailment of the circulatory system. Chronic obstructive lung diseases include emphysema, cystic fibrosis, and other conditions with widely differing causes that nonetheless all affect the same organ in the same way.

The remainder of the list includes two non-disease-related conditions (accidents at no. 5 and suicide at no. 8), three more noninfectious diseases (diabetes mellitus at no. 7, kidney disease at no. 9, and chronic liver disease and cirrhosis at no. 10); and just one infectious-disease-related set of causes. The latter, no. 6, consists of two diseases, pneumonia and influenza, which may be the result of another type of infection, the only infectious condition that poses a serious threat in the Western world today: AIDS, or acquired immunodeficiency syndrome.



Magnetic resonance imaging is one type of diagnostic test used to locate tumors. *(© Neal Preston/Corbis. Reproduced by permission.)*

Varieties of Disease

The essay Disease classifies noninfectious diseases as follows: hereditary or genetic diseases (e.g., hemophilia, discussed later in this essay); glandular diseases, or conditions involving a group of cells that filters material from the blood (e.g., diabetes mellitus, also included in the present essay); dietary diseases (see the essays Vitamins and Nutrients and Nutrition); cancers (discussed here); stress-related diseases (see Disease); autoimmune diseases (see Immunity and Immunology); and diseases of unknown origin (see Immunity and Immunology).

This is one way of dividing up ailments, and it happens to be the method applied in the essays of this book that deal with diseases. This method has the advantage of illustrating the wide variation in noninfectious diseases, but it would not necessarily be the best model to use for an in-depth professional study of disease. Scientists who study illnesses typically use one of several methods of classification that, while less broadly based than the one used here—and perhaps less interesting as well—are more efficient, because they group all diseases according to the same characteristics.

Some other classification systems. Among the systems doctors and scientists use for grouping diseases are topographic; anatomic; physiological; pathologic; etiologic, or causal; and epidemiological classifications. Topographic classification refers to bodily region or system: for instance, the circulatory system, the neurological system, and so on. The second method, anatomic (by organ or tissue), also uses parts of the body as a criterion for classification. The designation of heart and lung diseases, used earlier in discussing leading causes of mortality in the United States, is an example of this system.

Physiological classifications divide diseases in terms of function or effect (for example, metabolic disorders, some of which are discussed in Metabolism), while pathologic classifications separate diseases by the nature of the process that the disease takes: for example, inflammatory diseases. Etiologic, or causal, classifications are used most commonly in discussing infectious diseases, where broad types of causes can include viruses, bacteria, or other types of parasites. Likewise, epidemiological classifications usually refer to infectious diseases. Epidemiology is an area of the medical sciences devoted to the study of disease, including its incidence, distribution, and control within a population.

REAL-LIFE APPLICATIONS

Cancer

Although we are accustomed to hearing of "cancer" as though it were one disease, it is actually many diseases, close to 100 in number. Some of the most common varieties include skin, lung, and colon cancer, as well as breast cancer in women and prostate cancer in men. Blood and lymph node cancers, known as *leukemias* and *lymphomas,* respectively, are widespread, whereas cancer of the kidneys, ovaries, uterus, pancreas, bladder, and rectum are included among the cancers that most often affect Americans.

As this listing suggests, most cancers attack either body parts or systems and therefore are often classified anatomically or topographically; yet several characteristics unite these conditions. Cancer strikes the genes, which are carriers of genetic information that make up part of DNA (deoxyribonucleic acid), a molecule that appears in all cells. By gaining control at this level, the cancer is like a terrorist who has established a grip on all the communication or transportation systems in a country.

Many genes produce proteins that play a part in controlling the processes of cell growth and division. An alteration, or mutation, to the DNA molecule can disrupt the genes and produce faulty proteins, causing the cells to become abnormal and multiply. The abnormal cell begins to divide uncontrollably and eventually forms a new growth, known as a *tumor,* or neoplasm. In a healthy person, the immune system can recognize the neoplastic cells and destroy them before they have a chance to divide. Some mutant cells may escape immune detection, however, and survive to become tumors or cancers. (The immune system is discussed in Immunity and Immunology.)

Tumors can be either benign or malignant. A benign tumor is slow growing, does not spread or invade surrounding tissue, and, once removed, usually does not recur. A malignant tumor, on the other hand, invades surrounding tissue and spreads to other parts of the body. Therefore, even if the malignant tumor is removed, if the cancer cells have spread to the surrounding tissues, cancer will return. If the cancer cells are allowed to keep growing in number, migrating from the site of origin and spreading throughout the body, they eventually will kill the patient.

CAUSES AND TYPES. A majority of cancers are caused by changes in the cell's DNA because of damage from the environment. Environmental factors that are responsible for the initial mutation in DNA are called *carcinogens,* and there are many types, which we discuss shortly. Additionally, some cancers have a genetic basis: in other words, a person can inherit faulty DNA from his or her parents, which can predispose the patient to cancer of one kind or another. While there is scientific evidence that both factors (environmental and genetic) play a role, less than 10% of all cancers are purely hereditary.

There are several different types of cancers. In addition to leukemias and lymphomas, mentioned earlier, there are carcinomas, or cancers that arise in the epithelium (the layers of cells covering the body's surface and lining the internal organs and various glands). These types alone account for about 90% of all cancers. Some forms of skin cancer are melanomas, which typically originate in the pigment cells. Other forms of cancer include sarcomas (cancers of the supporting tissues of the body, e.g., bone, muscle, and blood vessels), and gliomas, or cancers of the nerve tissue.

DIAGNOSING CANCER. Many signs indicate the onset of cancer, among them, changes in the size, color, or shape of a wart or a mole; a sore that does not heal; or persistent cough, hoarseness, or sore throat. Many other diseases can produce similar symptoms, however, and for this reason it is important for a person to visit a doctor for regular checkups and diagnosis. Usually, diagnosis calls for fairly routine physical examination, though in the case of cancers of the reproductive organs, "routine" can still be plenty invasive.

Doctors examining women for cancers of the ovaries, uterus, cervix, and vagina must palpate the internal organs—that is, examine them by touch. For males, inspection of the rectum and the prostate is included in the physical examination. The doctor inserts a gloved finger into the rectum and rotates it slowly to feel for any growths, tumors, or other abnormalities. The doctor also palpates the testicles to identify any lumps, thickening, or differences in the size, weight, or firmness. Such examinations, as well as diagnoses for certain other types of cancer in private parts (namely, colon cancer), can be less

than pleasant, but they are certainly preferable to an early and painful death.

If the patient has an abnormality that could be indicative of cancer, the doctor may order diagnostic tests. These tests may include laboratory studies of sputum or saliva, blood, urine, and stool (feces). To locate tumors, such imaging tests as computerized tomography (CT) scans, magnetic resonance imaging (MRI), ultrasound, or fiber-optic scope examinations may be used. The most definitive diagnostic test, however, is the biopsy, in which a piece of tissue is surgically removed for examination under a microscope. Besides confirming whether a patient has cancer, the biopsy also provides information about the type of cancer, the stage it has reached, the aggressiveness of the cancer, and the extent of its spread.

Screening examinations, conducted regularly by health care professionals, can result in the detection of cancers at an early stage. In addition, advances in molecular biology (an area of biology concerned with the physical and chemical basis of living matter) and cancer genetics have led to the development of several tests for assessing one's risk of developing cancers. These new techniques include genetic testing, in which molecular probes are used to identify mutations in certain genes that have been linked to particular cancers. At present, however, there are limitations to genetic testing, a fact that emphasizes the need for better strategies of early detection.

TREATING CANCER. Although there is as yet no cure for cancer, there are treatments designed to remove as much of the tumor or tumors as possible and to prevent the recurrence or spread of the cancer. Cancer treatment can take many different forms, including surgery, radiation, chemotherapy, immunotherapy, hormone therapy, and bone-marrow transplantation. Physicians recommend specific treatments based on the needs, condition, and illness of the particular patient.

Surgery, the most frequently used form of cancer treatment, involves the removal of the visible tumor. It is most effective when a cancer is small and confined to one area of the body. Radiation, which kills tumor cells by bombarding them with high-energy waves or particles, may be used alone in cases where a tumor is unsuitable for surgery. More often, however, it is used in conjunction with surgery and chemotherapy or with drugs to kill cancer cells. While it can be highly effective, chemotherapy may be physically difficult for the patient and may have side effects, including temporary hair loss.

Immunotherapy uses the body's own immune system to destroy cancer cells. The various immunological agents being tested include substances produced by the body as well as vaccines. Unlike traditional vaccines, cancer vaccines do not prevent cancer; instead, they are designed to train the immune system of the cancer patient's body to attack and destroy cancer cells. Hormone therapy is standard treatment for some types of cancers that are hormone-dependent and which grow faster in the presence of particular hormones. Among them are cancers of the prostate, breast, and uterus, and the therapy is designed to block the production or action of the hormones involved.

A particularly aggressive form of treatment is bone-marrow transplantation, which involves taking tissue from within a donor's bone cavities, where blood-forming cells are located, and transplanting it into the patient. In addition, cancer patients may use massage, reflexology, herbal remedies, and other forms of treatment dubbed "alternative," meaning that they usually are not recognized by the mainstream of the medical profession. (Lack of official recognition does not necessarily mean anything: many people have benefited from alternative cancer treatments.)

Who Is at Risk?

One of every four deaths in the United States is from cancer, and each year more than a million Americans are diagnosed with some form of the disease. Of these people, about half will die of the disease. Cancer can attack anyone, even children, though, fortunately, cases of cancer in very young patients are the exception. Most cases are seen in middle-aged or older adults. Although scientists are a long way from being able to predict who will get cancer (much less effectively prevent it), they have identified numerous risk factors. A risk factor is not necessarily a cause per se (though it may be); rather, if there seems to be a link between a particular behavior and a specific disease, that behavior is referred to as a *risk factor* for that disease. Major risk factors for cancer are tobacco use, alcohol consumption, diet, certain types of sexual and reproductive behavior, infectious agents, family history, occupation, environment, and pollution.

SPECIFIC RISK FACTORS. Approximately two-fifths of all cancer deaths annually are linked to tobacco use and excessive alcohol consumption. In addition to the relationship between smoking and lung cancer (80–90% of all lung cancer patients are smokers), smoking also has been shown to be a contributory factor to a whole host of other cancers. Moreover, scientists have established that second-hand smoke (or passive smoking) can increase one's risk of cancer. Nor is "smokeless tobacco" a safe alternative to cigarettes: snuff and chewing tobacco have been associated with countless cases of mouth cancer.

Excessive drinking is a risk factor in liver cancer and other illnesses, and the deadly combination of tobacco *and* excessive alcohol use significantly increases the chances that a person will contract mouth, pharynx, larynx, or esophageal cancer. Tobacco and alcohol are not the only cancer-related agents that people take into their bodies: about one-third of all cancer deaths annually are related to the things people eat. For example, immoderate intake of fat, leading to obesity, has been associated with cancers of the breast, colon, rectum, pancreas, prostate, gallbladder, ovaries, and uterus.

There are even varieties of cancer that are linked to contagious diseases. Since the mid-1970s, scientists have obtained evidence showing that approximately 15% of all cancer deaths worldwide can be traced to viruses, bacteria, or parasites. One such pathogen, the human papilloma virus, is sexually transmitted. Having too many sex partners and becoming sexually active too early have been shown to increase one's chances of contracting cancer of the cervix. (On the other hand, women who do not have children or those who have them late in life have a higher risk of both ovarian and breast cancer.)

Certain cancers, including those of the breast, colon, ovaries, and uterus, recur generation after generation in some families, and therefore family history and genetics cannot be ruled out as risk factors. In addition, less well-known cancers, such as the eye condition known as retinoblastoma, have been traced to certain genes that can be tracked within a family. Thus, it is possible that inheriting particular genes makes a person susceptible to certain cancers.

OCCUPATION, ENVIRONMENT, AND POLLUTION. Cancers arising from occupational hazards make up a particularly significant group. They account for 4% of all cancer deaths, and there is a certain poignancy in the fact that these cancer victims contracted their illness not by drinking or smoking or bad eating but simply by earning a living. Nowhere was this poignancy more evident than in some of the first documented cases of cancer arising from occupational causes.

In 1775 the English surgeon Percivall Pott (1714–1788) described the high incidence of cancer of the scrotum among former chimney sweeps, most of them men in their twenties. This was bad enough, but the fact that they had contracted the cancer much earlier hinted at a reality even more grim. In the harsh early days of the Industrial Revolution, before child labor laws had even been imagined, boys as young as four—orphans or children of desperately poor families—were put to work cleaning the insides of chimneys. The chimneys were so narrow that only children could clean them, and because of the tight fit, even small boys were unable to wear any clothes while doing their job. As a result, soot became embedded in their skin, and, since few people bathed, it stayed there, a silent killer whose effects became apparent only many years later.

In addition to helping make English society aware of the injustices put upon members of its lowest classes, Pott's research introduced the medical world to the concept of occupational health. Still, until the last third of the twentieth century, large numbers of industrial workers in the West labored at occupations with built-in cancer hazards. Thus, asbestos workers contracted lung cancer at a high rate, and a link became apparent between bladder cancer and dye and rubber industries. Likewise, connections were established between skin or lung cancer and the jobs of smelters, gold miners, and arsenic workers; between leukemia and glue and varnish workers' occupations; between liver cancer and the business of PVC (polyvinyl chloride) manufacturers; and between lung, bone, and bone marrow cancer and the work of radiologists and uranium miners.

Radiation itself is an environmental hazard that affects not only workers in those specialized industries just named but also anyone who has been exposed to radioactive materials. Fortunately, this is less of a hazard today, thanks to numerous bans on nuclear testing; nonetheless, radiation—including ultraviolet radiation from



Portrait of young chimney sweepers from the 1890s. Before child labor laws, boys as young as four were put to work cleaning the insides of chimneys; many later contracted cancer of the scrotum from exposure to soot. *(© Bettmann/Corbis. Reproduced by permission.)*

the Sun—causes 1–2% of all cancer deaths. Additionally, it has been estimated that 1% of cancer deaths are due to air, land, and water pollution, particularly as a result of chemical dumping in water supplies.

Hemophilia

In contrast to the boys Pott treated, sufferers from hemophilia in the past often came from the highest echelons of society. A hereditary disease that primarily affects males, hemophilia was passed down through many royal lines, with the females acting as carriers and some of the males in the bloodline becoming victims of the disease. England's Queen Victoria (1819–1901) had several sons with hemophilia who died before they had the opportunity to become king. Her nephew, Russia's Czar Nicholas II, had a son who was hemophiliac as well. The boy's affliction caused his mother to seek the help of the charismatic "healer" Grigori Rasputin, whose close involvement with the royal family fed Russian discontent and helped contribute to the overthrow of the czar in 1917. (Ironically, the boy died not from hemophilia but perished, along with his family, before a Bolshevik firing squad.) Thus, once again (as noted in Disease), disease affected the course of history.

Its name taken from Greek and Latin words that together mean "love of bleeding," hemophilia



Alexis, son of Czar Nicholas II of Russia, had hemophilia, a hereditary disease that impairs the clotting of blood. The disease primarily affects males and has been passed down through many royal bloodlines. *(© Bettmann/Corbis. Reproduced by permission.)*

is caused by a genetic defect that prevents the body from developing proteins needed to help the blood clot. What would be a minor bruise or scratch for an ordinary person is therefore a life-threatening situation to a hemophiliac, who runs a severe risk of bleeding to death from even the most minor cut. A hemophiliac must therefore live in a state of constant fearfulness: as a youngster, for instance, he cannot run and jump and get into mischief like other boys, for fear that he might skin his knee—a minor pain for most boys but a serious injury to him. For hemophiliacs today, there is good news and bad news. The good news is that the condition can be treated with transfusions containing the necessary proteins, and this has extended the life expectancy of some victims. The bad news, however, is that in this day and age the treatment itself might kill them: the transfusions originate from donated blood, which may contain the virus that causes AIDS, as well as pathogens linked to other diseases.

Diabetes Mellitus

Much more prevalent than the genetic disorder hemophilia, or any one form of cancer, is diabetes mellitus, a serious condition caused by an absence of, or an insufficient amount of, insulin. Insulin, a hormone produced by the pancreas in varying amounts, helps maintain a normal concentration of glucose, or blood sugar (see Carbohydrates). Diabetes in general is a glandular disease, the gland in this case being the pancreas, but type 1 diabetes also is considered an autoimmune disorder because the body's own immune system destroys its insulin-producing cells. (See Immunity and Immunology and The Immune System for more about autoimmune disorders.)

Diabetes prevents the body from putting glucose to use, and instead large amounts of it are excreted in the urine. The word *diabetes* means "siphon," a reference to one of its major symptoms: frequent urination in an attempt to expel glucose. The urine itself is full of sugar; hence the term *mellitus,* meaning "honey." (In this vein, it is worth mentioning Chen Chuan, an eighth-century Chinese physician who surely qualifies as one of history's most dedicated scientists. He was the first to describe the sweetness of urine in patients suffering from diabetes, presumably as the result of firsthand research that went above and beyond the call of duty.)

Extent and types of diabetes. More than 12 million Americans, and some 100 million people worldwide, are affected by diabetes. That number is increasing by 5-6% annually, primarily the result of the population's increased longevity, combined with other factors such as increasing obesity and consumption of rich, processed, and carbohydrate-loaded foods (and drinks such as beer). Approximately 300,000 deaths each year are attributed to diabetes, which is of two principal varieties. Type 1, or insulin-dependent diabetes, is present at birth, is characterized by insulin deficiency, and normally is treated by taking insulin injections. Type 2, or non-insulin-dependent diabetes, arises not at birth, but somewhat later (though it can occur in childhood) and then among people who have normal insulin levels. (With type 2 diabetes, the problem is the body's inability to use its insulin efficiently.) Type 2, which typically stems from dietary causes—is preventable, but it is not treatable by insulin injections. Type 2 diabetes also may temporarily affect pregnant women, who may experience heightened glucose levels in a condition known as gestational diabetes. (There is another kind of diabetes altogether, a rare condition known as diabetes insipidus,

which involves inadequate production of another hormone, vasopressin.)

EFFECTS OF DIABETES. One might wonder why problems with blood sugar could be so serious as to kill a million people every three years and to qualify diabetes as one of the leading killers in America. The reason is that the body depends on glucose as a source of immediate energy, and in the absence of usable glucose, it begins instead to use its fat cells. This rapid burning of fat produces a surplus of organic compounds known as ketones, and ketone accumulation brings about an accumulation of acids in the blood, a condition known as ketoacidosis. Severe ketoacidosis can cause nausea, vomiting, and a loss of consciousness, or diabetic coma. If the patient does not receive a shot of insulin, he or she can die. Thus, the symptoms displayed by Julia Roberts's diabetic character in her first major movie, *Steel Magnolias* (1989), were not overdone. Diabetes can also bring about other conditions, including blindness, kidney diseases, and long-term organ damage.

THE TRIUMPH OF BANTING AND BEST. As difficult as life is for diabetics today, it is infinitely better than it was before 1921. That was the year when the Canadians Frederick Banting (1891–1941), a surgeon, and Charles Herbert Best (1899–1978), a physiologist, isolated insulin. Thanks to their work, and the subsequent development of insulin therapy—typically using insulin harvested from cows or pigs—deaths from ketoacidosis and diabetic coma declined. A person with type 1 diabetes, formerly consigned to a dramatically shortened life of misery, could hope to have something approaching a normal existence. Today diabetes remains a life-shortening illness, and doctors and scientists continue to search for a cure, but ever since 1921, the lot of those with diabetes has been improving steadily. (Banting was later knighted and shared the 1923 Nobel Prize in physiology and medicine for his achievement. Best, however, in one of history's great snubs, received neither honor, because he had not earned his doctorate at the time of the discovery.)

KEY TERMS

CARCINOGEN: A substance or agent that induces the development of cancer.

DISEASE: A general term for any condition that impairs the normal functioning of an organism.

DNA: Deoxyribonucleic acid, a molecule in all cells, and many viruses, containing genetic codes for inheritance.

EXTRINSIC: A term for a disease that is communicable or contagious and comes from outside the body. Compare with *intrinsic.*

GENE: A unit of information about a particular heritable (capable of being inherited) trait that is passed from parent to offspring and stored in DNA molecules called *chromosomes.*

GENETICS: The study of hereditary traits passed down from one generation to the next through the genes.

GLAND: A cell or group of cells that filters material from the blood, processes that material, and secretes it either for use again in the body or to be eliminated as waste.

INTRINSIC: A term for a disease that is not communicable or contagious and comes from inside the body. Compare with *extrinsic.*

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INFECTIOUS DISEASES

CONCEPT

The history of the human species, it has been said, is the history of infectious disease. Over the centuries, humans have been exposed to a vast amount and array of contagious conditions, including the Black Death and other forms of plague, typhoid fever, cholera, malaria, influenza, and the acquired immunodeficiency syndrome, or AIDS. Only in the past few hundred years have scientists begun to have any sort of accurate idea concerning the origin of such diseases, through the action of microorganisms and other parasites. Such understanding has led to the development of vaccines and methods of inoculation, yet even before they made these great strides in medicine, humans had an unseen protector: their own immune systems.

HOW IT WORKS

Infection and Immunity

There are two basic types of disease: ones that are infectious, or extrinsic, meaning that they are contagious or communicable and can be spread by contact between people, and ones that are intrinsic, or not infectious. Diseases in general and noninfectious diseases in particular are discussed in essays devoted to those subjects. So, too, is infection itself, a subject separate from infectious diseases: a person can get an infection, such as tetanus or salmonella, without necessarily having a disease that can be passed on through contact with others in the same way that colds, malaria, or syphilis is spread.

The background on scientists' progressive understanding of the microorganisms that cause disease and the means of fighting these microorganisms are discussed in Infection. Among the leading figures in that history were the French chemist and microbiologist Louis Pasteur (1822–1895) and the German bacteriologist Robert Koch (1843–1910), who contributed greatly to what is known today as germ theory—the idea that infection and infectious diseases are brought about by microorganisms. In most cases, the organisms are too small to be seen with the naked eye. They include varieties of amoeba and worm, discussed in the essay Parasites and Parasitology, as well as viruses and some forms of bacteria and fungi, which together are known as pathogens, or disease-carrying parasites. Other terms related to infectious diseases, their agents, and the prevention and study of them are defined in the essay Infection.

IMMUNE MECHANISMS. The human body has numerous mechanisms for protecting itself from infectious disease, the first line of defense being the skin. Skin shields us all the time from unseen attackers and generally is able to prevent pathogens from entering the body; however, any break in the skin, such as a cut or scrape, provides an opening for microorganisms to invade the body. Germs that normally would be prevented from entering the body are able to invade the bloodstream through such openings. This is why it is so very important, in any situation involving potential contact with infection, to protect the skin. With the advent of AIDS, doctors and members of other professions who are likely to touch people carrying diseases—including officers arresting addicts or prostitutes—are much more likely to do their work wearing heavy plastic gloves.

Suppose that a microorganism makes it through the barrier of skin, thanks to a cut or other opening; if so, the body puts into action a second defensive mechanism, the immune system. This system is a network of organs, glands, and tissues that protects the body from foreign substances. Without a properly functioning immune system, a person could die simply by walking out the door in the morning and coming into contact with an airborne infectant. Even in relatively healthy people, the immune system may be unable to react adequately to an invasion of microorganisms. In such cases, disease develops.

Transmission of Diseases

Infectious diseases, by definition, are transmitted easily from one person to another. We have all been told, for instance, not to drink after someone who has a cold. On a much more serious level, persons who are sexually active or potentially sexually active, but not settled in a monogamous (one-partner) relationship, are advised to avoid unprotected sexual contact so as not to contract AIDS or some other sexually transmitted disease (STD). In these and many other cases, microorganisms travel from the carrier of the disease to the uninfected person. (Actually, in the case of AIDS, the pathogen is a virus, which is not, strictly speaking, an organism or even a living thing; however, viruses usually are lumped in with bacteria, amoeba, and some fungi as microorganisms.)

Pathogens can be spread by many methods other than direct contact, including through water, food, air, and bodily fluids—blood, semen, saliva, and so on. For instance, any time a person with an infection coughs or sneezes, they may be transmitting illness. This is how diseases such as measles and tuberculosis are passed from person to person. AIDS and various STDs, as well as many other conditions, such as hepatitis, are transferred when one person comes into contact with the bodily fluids of another. This is the case not only with sexual intercourse but also with blood transfusions and any number of other interactions, including possibly drinking after someone. (Contrary to rumors that circulated in the early 1980s, when AIDS first made itself known, that particular syndrome cannot be transferred by saliva, but the common cold and other viral infections can be.)

Cholera, caused by a bacterium found in dirty wells and rivers from India to England (in the 1800s, at least), is an example of a waterborne disease. Many foodborne pathogens tend to bring about what would be more commonly thought of as an illness than a disease, since in everyday language the latter term implies a long-term affliction, whereas food poisoning usually lasts for a week or so. (Still, some forms of food poisoning can be fatal.) Bacterial contamination may occur when food is not cooked thoroughly, is left unrefrigerated, is prepared by an infected food handler, or otherwise is handled in an unsanitary or improper fashion. (The case of Typhoid Mary, discussed near the conclusion of this essay, is an extreme example of this form of transmission.)

Additionally, diseases may be transferred by vectors—animals (usually insects) that carry microorganisms from one person to another. Vectors may spread a disease either by mechanical or by biological means. Mechanical transmission occurs, for example, when flies transfer the germs for typhoid fever from the feces (stool) of infected people to food eaten by healthy people. Biological transmission takes place when an insect bites a person and takes infected blood into its own system. Once inside the insect's gut, the disease-causing organisms may reproduce, increasing the number of parasites that can be transmitted to the next victim. This is how the *Anopheles* mosquito vector, for instance, transfers malaria.

Real-Life Applications

A Tour of Diseases

The range of infectious diseases, from conditions that merely cause discomfort to those that bring about death, is truly staggering. Some have brought about vast epidemics that have wiped out huge populations, and many have changed the course of history, while others are hardly known to anyone outside the ranks of epidemiologists and the victims of the disease. Some, such as smallpox, have been eradicated or largely eradicated through inoculation campaigns, while others, most notably AIDS, continue to elude efforts to defeat them.

Diseases can be classified according to the systems or body parts affected. Some of those

systems and parts, with examples of diseases relating to each, include the following.

- Upper respiratory tract: common cold, sinusitis, croup
- Lower respiratory tract: pneumonia, bronchitis
- Cardiovascular system: rheumatic fever
- Central nervous system: meningitis, encephalitis
- Genitourinary tract: sexually transmitted diseases (i.e., venereal diseases, such as syphilis, gonorrhea, and the herpes simplex viral infection)
- Gastrointestinal tract: cholera, salmonella, hepatitis
- Bones and joints: septic arthritis
- Skin: warts, candida
- Eyes: conjunctivitis (pink eye)

Another way to classify diseases is according to the types of organism that cause them: bacteria, viruses, or other forms of parasite, particularly worms, amoeba, and insects. The first two groups are discussed in further detail within Infection and the other varieties of parasite in Parasites and Parasitology.

Bacterial infections include anthrax, botulism, tetanus (lockjaw), leprosy, tuberculosis, diphtheria, whooping cough, plague, and a variety of pneumococcal, staphylococcal, and streptococcal illnesses. Among viral illnesses and diseases are the common cold, influenza, infectious mononucleosis, smallpox, chicken pox, measles, mumps, rubella (or German measles), yellow fever, poliomyelitis (i.e., polio), rabies, herpes simplex, and AIDS. Diseases related to other varieties of parasite include malaria, Rocky Mountain spotted fever, trichinosis, scabies, and river blindness. Nonmicroscopic parasites, particularly such worms as hookworm and pinworm, bring about disease-like forms of parasitic infestation within the body.

Plagues

From earliest times infectious diseases have wreaked havoc on the human species, and this was particularly so with the various plagues that struck Europe in ancient and medieval times. As noted in Infection, a plague in the fifth century B.C. helped bring an end to the golden age of Greek civilization. A thousand years later, another plague befell Greece, which by then dominated what remained of the Roman Empire. Based in Byzantium (Constantinople) this realm became known to history as the Byzantine (Eastern Roman), Empire, though its citizens saw themselves simply as "Romans" and thus as the inheritors of Roman civilization. Italy itself had fallen under the control of nomadic invaders, the Visigoths, but Emperor Justinian I (483–565) undertook a vast and costly campaign to wrest control of the Italian peninsula from the barbarians. Had he succeeded, the entire course of medieval history in Western Europe might have been different; he did not, largely because of a plague that swept Constantinople in 541.

Through a series of interconnected events, the plague permanently weakened Byzantium and left the Mediterranean world ripe for conquest by a new power: Islam. Both directly and indirectly, the plague of 541 served to divide Eastern and Western Europe. Not only was the Roman Empire never truly reunited, meaning that the two halves of the continent grew increasingly separate, but the rise of Islam made possible the Crusades (1095–1291). The latter sowed further discord between the East and the West, owing to the fact that Western European crusaders overran Byzantium and incited trouble between the Byzantines and Arabs. Ultimately, the split between Eastern and Western Europe, which became particularly pronounced during the years of Communism and the Iron Curtain (1945–1990), can be traced to the plague of 541.

The Black Death

The Byzantine plagues (there were several, occurring at intervals of a few generations), killed millions of people, yet for sheer scope of destruction—and, perhaps, historical impact—they were dwarfed by the plague that devastated Europe in the years 1347–1351. This one became known as the Plague (with a capital *P*) or by another name that gave some hint of the terror that was as much a part of the epidemic as the ghastly physical symptoms it brought on: the Black Death.

It began in Asia and quickly made its way to the shores of the Black Sea, where it erupted in September 1346. The first outbreak in Western Europe occurred 13 months later, in October 1347, at the Sicilian port of Messina, from whence it was an easy jump to the Italian mainland. By the following April all of Italy was infected; meanwhile, the Plague had reached Paris in



A political cartoon from about 1870 illustrates the unsanitary conditions in New York City, with the politician and public works commissioner Boss Tweed welcoming a cholera epidemic. *(© Bettmann/Corbis. Reproduced by permission.)*

January 1348, and within a year, 800 people a day were dying in that city alone. Quickly it penetrated the entire European continent and beyond, from North Africa to Scandinavia and from England to the hinterlands of Russia. By 1351 it had spread so far and wide that sailors arriving in Greenland found its ports deserted.

The only merciful thing about the Black Death was that death came quickly. Victims typically died within four days—a hundred hours of agony. If they caught a strain of bubonic plague, their lymph glands swelled; if it was pneumonic plague, the lungs succumbed first. Either way, as the end approached, the victim turned purplish-black from respiratory failure—hence the name Black Death.

SOCIAL IMPACT OF THE PLAGUE. Lacking any modern concept of what causes disease, people looked for spiritual explanations. Some believed that the world was coming to an end, while others joined sects of flagellants, religious enthusiasts who wandered the countryside, beating themselves with lashes as a way of doing penance. The flagellants were tied closely tied to a rising trend toward anti-Semitism: searching for someone to blame, Europeans found a convenient scapegoat in the Jews, who, they claimed, had started the Plague by poisoning the wells of Europe.

The Black Death aptly illustrates how infectious diseases can have an impact on history in ways both big and small. In just five years the disease killed about 30% of Europe's population, which had been 100 million in 1300 but which would not reach that level again until 1500. All over the continent, farms were emptied and villages abandoned, leading to scarcity and higher prices. In the short run, these economic conditions spurred peasant revolts, but in the long run, the shortage of workers brought about higher wages and contributed to the emergence of the working and middle classes. Neither popes nor priests, neither kings nor noblemen, were any more equipped than the common people to confront the fearsome disease, and this, too, helped provoke the rise of competing classes and new centers of power in European society.

THE ETIOLOGY OF THE PLAGUE. The Black Death, in short, may be regarded as the beginning of the end of the Middle Ages—a hideously painful event that nevertheless carried positive consequences, which might hardly have been achieved without it. The irony was that the force at the center of all this devastation and change was too small to be seen by the naked eye. Although the disease was carried by rats, the cause of the Black Death was actually a bacillus known today as *Pastuerella pestis* or *Yersinia pestis,* which uses fleas as a vector. Modern medicines such as streptomycin, a variety of antibiotic developed after World War II, would have stopped the Plague, but such concepts were a long time in coming. Although the worst phase of the epidemic ended in 1351, it continued to spread, reaching Moscow by 1353; the next five centuries saw occasional outbreaks of the disease. As late as 1894 a strain of plague killed more than six million people in Asia over the course of 14 years.

The Changing Face of Disease

The many biblical passages dealing with leprosy illustrate the role that infectious disease has played in human life from the earliest times. The fact that leprosy causes the victim's skin to turn ghostly white and brings about a gradual withering away of body parts must certainly have seemed like a curse from God. In fact, leprosy, also known as Hansen disease, is caused by the bacillus *Mycobacterium leprae,* and despite the many fears throughout the ages associated with touching lepers, it is not very contagious. A scene in the 1973 blockbuster *Papillon* illustrates this fact. The title character, a prison escapee played by Steve McQueen, takes a drag from a cigar offered to him by a leper, who then asks him if he knew that leprosy is not contagious. Papillon says no, indicating that he simply intended to build a sense of shared risk with someone who he hoped would aid his escape.

The example of leprosy shows something about the many curiosities involved in diseases and their study: for example, the fact that a disease can be infectious without being significantly contagious. Leprosy is by definition infectious, inasmuch as it is caused by a pathogen known as *Mycobacterium leprae,* but the latter is unusual for a number of reasons, including the fact that it is extremely slow in dividing, unlike most bacteria. After years of study, researchers are still not clear as to how leprosy is transmitted, and many believe that genetics may play a role. Thanks to increased understanding of the disease, the stigma that used to go with leprosy—including the reference to people with the disease as "lepers"—has largely been lifted. Yet places such as the leprosy facilities at Carville, Louisiana, and Molokai, Hawaii, continued to exist for many years, if only because the disfigurement associated with the disease influenced the separation of leprosy sufferers from the rest of society. In 1998, with only about 6,000 victims of the disease left in the entire country, the federal government closed the facilities at Carville and Molokai.

Leprosy remains a threat, with some two million cases of the disease worldwide, primarily in nations of Asia, Africa, and Latin America that are both underdeveloped and located in tropical zones. It has, however, ceased to be the worldwide danger that it once was, and as such it joins ranks with numerous other afflictions that formerly held all of humankind in the grip of terror. For example, tuberculosis, caused by a bacillus that attacks the lungs, afflicted a huge population in the nineteenth century, bringing an end to the careers of figures that ranged from the great English poet John Keats to the American gunslinger Doc Holliday. Holliday, in fact, traveled to Tombstone, Arizona, where he and Wyatt Earp participated in the infamous shootout at the O.K. Corral, because he thought the climate would help his condition. Their story has been portrayed in countless films; for example, in *Tombstone* (1993), Val Kilmer gives an extremely convincing



Leprosy, caused by the bacillus Mycobacterium leprae, brings about a gradual withering away of body parts. There are some two million cases of the disease worldwide, primarily in the underdeveloped nations of Asia, Africa, and Latin America. *(© Paul A. Souders/Corbis. Reproduced by permission.)*

portrayal of the debilitating effects that Holliday's tuberculosis (aggravated by his lifestyle) must have had on him. Today, tuberculosis is not nearly the scourge that it once was, though it remains a problem, particularly because of patients' increasing resistance to the antibiotics used to treat it. (See Infection for more about antibiotics.)

VACCINATION AND CONTINUING THREATS. When Europeans invaded the lands of Native Americans, they brought with them a host of microorganisms to which they had developed an immunity but to which the Indians were completely vulnerable. Although Europeans and their descendants had developed immunities to various diseases, thanks to generations of exposure to pathogens, they and the rest of the world remained vulnerable to a host of contagious disease, including cholera, smallpox, chicken pox, measles, mumps, yellow fever, polio, malaria, and many others. Today, vaccines have virtually eradicated many of these contagious diseases and keep others at bay. (Anyone who has ever had a cholera vaccine, which causes the patient's body to become miserably sore, achy, and tender for about 48 hours, has some idea of just how awful the disease itself must be.) Polio, which once posed an enormous threat to American children and crippled one of America's greatest leaders, President Franklin D. Roosevelt, is an artifact of history, thanks to vaccines developed after World War II.

Yet some killers never really die. For instance, malaria, caused by a protozoan parasitic genus known as *Plasmodium* and spread by mosquito biological vectors, infects from 300 to 500 million people annually and kills up to 2.7 million people every year. Although the substance known as quinine showed some promise as a treatment during most of the nineteenth and twentieth centuries, Plasmodium has become increasingly resistant to it. In the search for a cure for what has been called "the most devastating disease in history," some 100,000 drugs have been tested.

Some Other Killers

The twentieth century saw its own version of the Plague, in the form of the 1918–1920 influenza epidemic. Carried to all corners of the globe by soldiers returning from World War I, "the Influenza," as it came to be known (again with a capital letter to distinguish it as the greatest outbreak of a particular disease), killed 20 million



Following the September 11, 2001, terrorist attacks on the United States, a series of letters containing anthrax spores showed up around the country, and exposure to the disease led to a handful of deaths. In one incident hazardous materials experts were called to Capitol Hill to investigate. *(© AFP/Corbis. Reproduced by permission.)*

people—more than the war itself. Then there is the greatest epidemic of the latter part of the twentieth century and the early twenty-first century: AIDS. This disease is linked to the human immunodeficiency virus (HIV), a retrovirus (see Infection for an explanation of retrovirus) that causes a gradual breakdown of the victim's immune system.

People do not die of AIDS per se but of the illnesses—particularly pneumonia or Kaposi's sarcoma, a cancer of the tissues—to which AIDS makes them susceptible. The disease is transmitted primarily by sexual contact and intravenous drug use. A smaller number of particularly tragic cases result from no actions on the part of the victim, who in this case is either the recipient of infected blood or the child of a mother with AIDS. Since the disease first came to public attention in 1981, 21.8 million people worldwide (and about 750,000 in the United States) have died from it. The vast majority of deaths have been in sub-Saharan Africa, and 90% of all AIDS cases are in developing countries. Worldwide, approximately 36.1 million people have either HIV or AIDS. (For more about AIDS, see Immunity and Immunology.)

THE EBOLA VIRUS. AIDS was not the only infectious condition to come out of central Africa and terrorize the world in the late twentieth century. Beginning in about 1975, numerous viruses, previously unknown and terrifyingly lethal, emerged from tropical regions of Africa, South America, and Asia. So great was the rise of new infectious diseases that some epidemiologists believed this was tied with economic development: as humans cultivated previously undeveloped lands and delved into more isolated parts of the world, they might be exposing new viruses.

Few of these inspired as much terror as the Ebola virus, and the fear is understandable, given the effects of the disease. Three to nine days after the illness enters the body, the victim begins to experience fever and other flu-like symptoms, sudden exhaustion, sore throat, muscle pain, and headache. Vomiting and diarrhea soon follow, and the vomit and stools are black with blood. Soon hemorrhaging occurs, with blood flowing from the nose, ears, and even the eyes. Internal organs begin to liquefy, and within three weeks of contracting the virus, the victim is usually dead.

An almost unbelievably hideous condition, Ebola might seem at first glance a great deal like the Black Death. Why, then, has it not ravaged whole populations the way the Plague did? It is certainly not because scientists have a cure for Ebola; the best doctors can hope to do, if they detect the disease early enough, is to provide supportive care, such as blood transfusions, that may save the patient's life. Yet even the worst outbreaks of the disease have not occurred on anything like the scale of the Plague: the worst known outbreak of Ebola, in Uganda in 2000–2001, killed 425 people.

Part of the reason Ebola is not capable of spreading rapidly is, ironically, because it is such an efficient killer: it kills its human victims before they have a chance to spread it to many other victims. Other than nonfatal incidents in laboratories in the United States, England, and Italy, as well as one case in a monkey export facility in the Philippines—various primates are carriers—all Ebola cases and outbreaks have been in Africa, primarily in Zaire (now Democratic Republic of the Congo), Sudan, and Gabon. Many times, local conditions, situations, and practices have

exacerbated the spread of the disease. For example, in 1996, a group of people in Gabon found a dead chimpanzee in the forest and ate it; as a result, 37 people died. The Uganda outbreak became much worse than it might have been because locals, lacking education as to antiseptic procedures, failed to take proper precautions. Many died as a result of attending funerals of Ebola victims at which bodies were not disposed of properly.

TYPHOID MARY. Sometimes a single person can be a walking epidemic, as in the case of the Irish cook Mary Mallon (1869–1938), better known as "Typhoid Mary." Mallon was an example of the fact that some people, because of genetic characteristics or other specifics, can act as carriers of a disease without ever contracting it themselves. Even though Typhoid Mary had *Salmonella typhosa* bacteria in her system, she did not get sick; still, she was highly contagious, and her profession as cook made her particularly dangerous. At least three deaths and 53 cases of typhoid fever were linked directly to her, with thousands of other probable cases of infection indirectly caused by this human vector.

Part of what made her so notorious—hence her nickname, given to her by the press—was the fact that Mallon did not seem to care how many people she infected. In the first decade of the twentieth century, authorities tracked her down as the cause of, or at least a contributing factor in, an outbreak of typhoid in the New York City area. Instead of cooperating with officials, Mallon repeatedly escaped before being caught and confined to Riverside Hospital on New York's North Brother Island in 1910. She served three years in isolation there before her release, after which she promptly went back to work as a cook—despite explicit orders not to do so. It was this (and an outbreak of typhoid fever at her place of work, which happened to be a hospital) that earned her the nickname by which she became known to history. She was caught again in 1915 and spent the remainder of her life on North Brother Island.

THE THREAT OF BIOLOGICAL WARFARE. Infinitely more despicable than Typhoid Mary are terrorists and rogue nations that would willingly unleash infectious disease on large, unsuspecting civilian populations. One such pathogen is *Bacillus anthracis,* the cause of anthrax, a deadly bacterial disease of cattle and other grazing animals. Under the right circumstances, anthrax can kill a human in about 36 hours, though a number of antibiotic treatments are effective in the early stages of the disease.

During the late twentieth century, the United States and Soviet Union experimented with

KEY TERMS

EXTRINSIC: A term for a disease that is communicable or contagious and comes from outside the body. Compare with *intrinsic.*

GERM THEORY: A theory in medicine, widely accepted today, that infections, contagious diseases, and other conditions are caused by the actions of microorganisms.

IMMUNE SYSTEM: A network of organs, glands, and tissues that protects the body from foreign substances.

IMMUNITY: The condition of being able to resist a specific disease, particularly through means that prevent the growth and development or counteract the effects of pathogens.

INFECTION: A state or condition in which parasitic organisms attach themselves to the body or to the inside of the body of another organism, causing contamination and disease in the host.

INTRINSIC: A term for a disease that is not communicable or contagious and comes from inside the body. Compare with *extrinsic.*

PATHOGEN: A disease-carrying parasite, usually a microorganism.

STD: Sexually transmitted disease.

VECTOR: An organism, such as an insect, that transmits a pathogen to the body of a host.

the use of anthrax in biological warfare, and an accidental release of anthrax spores at a Soviet lab in 1979 led to some 68 deaths. Following the September 11, 2001, terrorist attacks on the World Trade Center in New York City and on the Pentagon, a series of letters containing anthrax spores showed up around the United States, and exposure to the disease led to a handful of deaths. Although the attacks were linked initially to Osama bin Laden and his al-Qaeda organization, authorities increasingly began to suspect that home-grown terrorists were simply exploiting the September 11 attacks as cover for their own deeds.

Still, there was little doubt that bin Laden, the Iraqi dictator Saddam Hussein, or North Korea's ruling clique would use biological agents if the opportunity arose. One threat that loomed in the aftermath of September 11 was the possibility that bin Laden's followers would reintroduce the smallpox virus, which had been eradicated by worldwide vaccinations during the 1970s. The reason why smallpox could pose such a great threat is precisely that it has been eliminated, and few Americans born after 1973 have received vaccines. Unless they gained access to one of the two labs worldwide (one in the United States and one in Russia) where smallpox virus is stored for the purpose of making vaccines, however, terrorists would be unable to obtain a sample. (It is this matter of access that led authorities to suspect that the anthrax attacks were an "inside job.")

Another biological agent that poses a threat is *Clostridium botulinum,* which causes botulism, a toxic condition that can result in paralysis. Members of the fanatic Japanese cult Aum Shinrikyo attempted unsuccessfully to launch botulism attacks in Tokyo on three occasions in 1995. The Japanese government itself—that is, the Axis Japanese government of World War II—experimented with another biological agent, tularemia, or *Francisella tularensis.* The pathogen, which causes lung inflammation and death, is considered one of the most dangerous forms of biological weapon, because it is extremely efficient and easy to spread. America's military, borrowing an idea from its former enemy, developed its own *F. tularensis* strain in the late 1960s but destroyed its stockpile in 1973.

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IMMUNITY

IMMUNITY AND IMMUNOLOGY

THE IMMUNE SYSTEM

IMMUNITY AND IMMUNOLOGY

CONCEPT

Immunity is the condition of being able to resist a specific disease, particularly through means that prevent the growth and development of disease-carrying organisms or counteract their effects. It is regulated by the immune system, a network of organs, glands, and tissues that protects the body from foreign substances. Immunology is the study of the immune system, immunity, and immune responses. Progress in immunology over the past two centuries has made inoculation—the prevention of a disease by the introduction to the body, in small quantities, of the virus or other microorganism that causes the disease—widely accepted and practiced. Despite such progress, however, some diseases evade human efforts to counteract them through medicine or other forms of treatment. This is particularly the case with a disease in which the immune system shuts down entirely: a condition known as acquired immunodeficiency syndrome, or AIDS.

HOW IT WORKS

Immunity and the Immune System

The functioning of the immune system is considered in a separate essay, along with the means by which that system responds to foreign invasion. Also included in that essay is a discussion of allergies, which arise when the body responds to ordinary substances as though they were pathogens, or disease-carrying parasites. The body cannot know in advance what a pathogen will look like and how to fight it, so it creates millions and millions of different lymphocytes, a type of white blood cell. The principal types of lymphocyte are B cells and T cells. These cells recognize random antigens, or substances capable of requiring an immune response.

Certain researchers believe that while some B cells and T cells are directed toward fighting an infection, others remain in the bloodstream for months or even years, primed to respond to another invasion of the body. Such "memory" cells may be the basis for immunities that allow humans to survive such plagues as the Black Death of 1347–1351 (see Infectious Diseases). Other immunologists, however, maintain that trace amounts of a pathogen persist in the body and that their continued presence keeps the immune response strong over time.

Immunology

Immunology is the study of how the body responds to foreign substances and fights off infection and other disease-causing agents. Immunologists are concerned with the parts of the body that participate in this response, and this investigation takes them beyond looking merely at tissues and organs to studying specific types of cells or even molecules.

From ancient times, humans have recognized that some people survive epidemics, when the majority are dying. About 1,500 years ago in India, physicians even practiced a form of inoculation, as we discuss later. The modern science of immunology, however, had its beginnings only in 1798, when the English physician Edward Jenner (1749–1823) published a paper in which he maintained that people could be protected from the deadly disease smallpox by the prick of a needle dipped in the pus from a cowpox boil. (Cow-

pox is a related, less-lethal disease that, as its name suggests, primarily affects cattle.)

Later, the great French biologist and chemist Louis Pasteur (1822–1895) theorized that inoculation protects people against disease by exposing them to a version of the pathogen that is harmless enough not to kill them but sufficiently like the disease-causing organism that the immune system learns to fight it. Modern vaccines against such diseases as measles, polio, and chicken pox are based on this principle.

HUMORAL AND CELLULAR IMMUNITY. In the late nineteenth century, a scientific debate raged between the German physician Paul Ehrlich (1854–1915) and the Russian zoologist Élie Metchnikoff (1845–1916) concerning the means by which the body protects against diseases. Ehrlich and his followers maintained that proteins in the blood, called antibodies, eliminate pathogens by sticking to them. This phenomenon and the theory surrounding it became known as humoral immunity. Metchnikoff and his students, on the other hand, had noted that certain white blood cells could swallow and digest foreign materials. This cellular immunity, they claimed, was the real way that the body fights infection. In fact, as modern immunologists have shown, both the humoral and cellular responses identified by Ehrlich and Metchnikoff, respectively, play a role in fighting disease.

REAL-LIFE APPLICATIONS

Inoculation and Vaccines

Inoculation is the prevention of a disease by the introduction to the body, in small quantities, of the virus or other microorganism that causes that particular ailment. It is a brilliant idea, yet one that seems to go against common sense. For that reason, it was a long time in coming: not until the time of Jenner, in about 1800, did the concept of inoculation become widely accepted in the West. Nonetheless, it had been applied more than 13 centuries earlier in India.

In the period between about 500 B.C. and A.D. 500, Hindu physicians made extraordinary strides in a number of areas, pioneering such techniques as plastic surgery and the use of tourniquets to stop bleeding. Most impressive of all was their method of treating smallpox, which remained one of the world's most deadly diseases until its eradication in the late 1970s. Indian physicians apparently took pus or scabs from the sores of a mildly infected patient and rubbed the material into a small cut made in the skin of a healthy person. The Indians' method was risky, and there was always a chance that the patient would become deathly ill, but the idea survived and gradually made its way west over the ensuing centuries.

SMALLPOX VACCINATION. Smallpox, or variola, is carried by a virus that causes the victim's body to break out in erupting, pus-filled sores. Eventually, these sores dry up, leaving behind scars that may alter the appearance of the victim permanently, depending on the intensity of the disease. Such was the case with Lady Mary Wortley Montagu (1689–1762), a celebrated English writer and noblewoman. Known for her passionate relationships, romantic and otherwise, Lady Montagu had been scarred from youth by smallpox, and no doubt this experience gave her heightened concern for the victims of the disease. While she was in Turkey with her husband, Edward, an ambassador, she became aware of an inoculation method, probably based on the Hindu practice of many centuries before, used by local women. Lady Montagu arranged for her three-year-old son to be inoculated against smallpox in 1717, and after returning home, initiated smallpox inoculations in England.

Nonetheless, the problem remained that the inoculated person contracted a serious case of the disease and died, at least some of the time. More than 80 years later, in 1796, during a smallpox epidemic, Jenner decided to test a piece of folk wisdom to the effect that anyone who contracted cowpox became immune to human smallpox. He took cowpox fluid from the sores of a milkmaid named Sarah Nelmes and rubbed it into cuts on the arm of an eight-year-old boy, James Phipps, who promptly came down with a mild case of cowpox. Soon, however, James recovered, and six weeks later, when Jenner injected him with samples of the smallpox virus, the boy was unaffected.

Jenner, who published his findings after conducting additional tests, coined a new term for the type of inoculation he had used: *vaccination,* from the Latin word for cowpox, *vaccinia.* (The



The modern science of immunology had its beginnings in 1798, when the English physician Edward Jenner published a paper in which he maintained that people could be protected from the deadly disease smallpox by the prick of a needle dipped in the pus from a cowpox boil. *(© Bettmann/Corbis. Reproduced by permission.)*

latter term comes from the Latin *vacca,* or "cow," the source of such terms as the French *vache.*) With the success of his vaccine, Jenner was awarded a sum of money to continue his work, and he soon oversaw the vaccination of thousands of English citizens, including the royal family. The practice spread to Germany and Russia and then to the United States. In Lady Montagu's time, the American clergyman Cotton Mather (1663–1728) had been an advocate of vaccination, and now President Thomas Jefferson (1743–1826) became an ardent proponent of Jenner's methods.

RABIES AND POLIO INOCULATION. The next advancement in the study of vaccines came almost 100 years after Jenner's discovery. In 1885 Pasteur saved the life of Joseph Meister, a nine-year-old boy who had been attacked by a rabid dog, by using a series of experimental rabies vaccinations. Pasteur's rabies vaccine, the first human vaccine created in a laboratory, was made from a version of the live virus that had been weakened by drying it over potash (sodium carbonate—burnt wood ashes).

Exactly 70 years later, the American microbiologist Jonas Salk (1914–1995) created a vaccine for poliomyelitis (more commonly known as polio), in which the skeletal muscles waste away and paralysis and often permanent disability and deformity ensue. Although polio had been known for ages, the first half of the twentieth century had seen an enormous epidemic in the United States.

The most famous victim of this scourge was the future president Franklin D. Roosevelt (1882–1945), who contracted it while on vacation in 1921. Throughout the 1930s and 1940s, polio remained a threat, especially to children; at the peak of the epidemic, in 1952, it killed some 3,000 Americans in one year, while 58,000 new cases were reported. At the same time, Salk was working on his vaccine, which finally was declared safe after massive testing on schoolchildren. In 1961 an oral polio vaccine developed by the Polish-born American virologist Albert Sabin (1906–1993) was licensed in the United States. Whereas the Salk vaccine contained the killed versions of the three types of poliovirus that had been identified in the 1940s, the Sabin vaccine used weakened live poliovirus. Because it was taken by mouth, the Sabin vaccine proved more convenient and less expensive to administer than the Salk vaccine, and it soon overtook

the latter in popularity. By the early 1990s health organizations reported that polio was close to extinction in the Western Hemisphere.

TRIUMPHS AND CONTINUING CHALLENGES. Thanks to these and other vaccines, many life-threatening infectious diseases have been forced into retreat. In the United States, children starting kindergarten typically immunized against polio, diphtheria, tetanus, measles, and several other diseases. Other vaccinations are used only by people who are at risk of contracting a disease, are exposed to a disease, or are traveling to an area (usually in the Third World) where particular diseases are common. Such vaccinations include those for influenza, yellow fever, typhoid, cholera, and hepatitis A.

Internationally, 80% of the world's children had been inoculated as of 1990 for six of the primary infectious diseases: polio, whooping cough, measles, tetanus, diphtheria, and tuberculosis. Smallpox was no longer on the list, because efforts against it had proved overwhelmingly successful. (See Infectious Diseases for more on the threat, or nonthreat, of smallpox as a form of biological warfare.) Despite these successes, however, each year more than two million children who have not received any vaccinations die of infectious diseases. Even polio has continued to be a threat in some parts of the world: as many as 120,000 cases are reported around the world each year, most in developing regions. And as if the threat from age-old diseases were not enough, in the last quarter of the twentieth century a new killer entered the fray: AIDS.

AIDS

A viral disease that is almost invariably fatal, AIDS destroys the immune systems of its victims, leaving them vulnerable to a variety of illnesses. No cure has been found and no vaccine ever developed. The virus that causes AIDS has proved to be one of the most elusive pathogens in history, and so far the only effective way not to contract the disease is to avoid sharing bodily fluid with anyone who has it. This means not having sex without condoms (and, to be on the truly safe side, not having sex outside a committed, fully monogamous relationship) and not engaging in intravenous drug use. But there are some people who have contracted the AIDS virus through no actions or fault of their own: people who have received it in blood transfusions or, even worse, babies whose AIDS-infected mothers have passed the disease on to them.

Within two to four weeks of being infected with the virus that causes AIDS (HIV, human immunodeficiency virus), a patient will experience what at first seems like flu: high fever, headaches, sore throat, muscle and joint pains, nausea and vomiting, open ulcers in the mouth, swollen lymph nodes, and perhaps a rash. As the immune system begins to fight the invasion, some cells produce antibodies to neutralize the viruses that are floating free in the bloodstream. Killer T cells destroy many other cells infected with the AIDS virus, and the patient enters a phase of the disease in which no symptoms are evident.

Although at this point it seems as though the worst is over, in fact, the AIDS virus is at work on the immune system, quietly destroying the body's protection by infecting those T cells that would protect it. With an immune system that gradually becomes more and more unresponsive, the patient is made vulnerable to any number of infections. Normally, the body would be able to fight off these attacks with ease, but with the immune system itself no longer functioning properly, infectious diseases and cancers are free to take over. The result is a long period of increasing misery and suffering, sometimes accompanied by dementia or mental deterioration caused by the ravaging of the brain by disease. Whatever the course it takes, the end result of AIDS is always the same: not just death but a miserable, excruciatingly painful death.

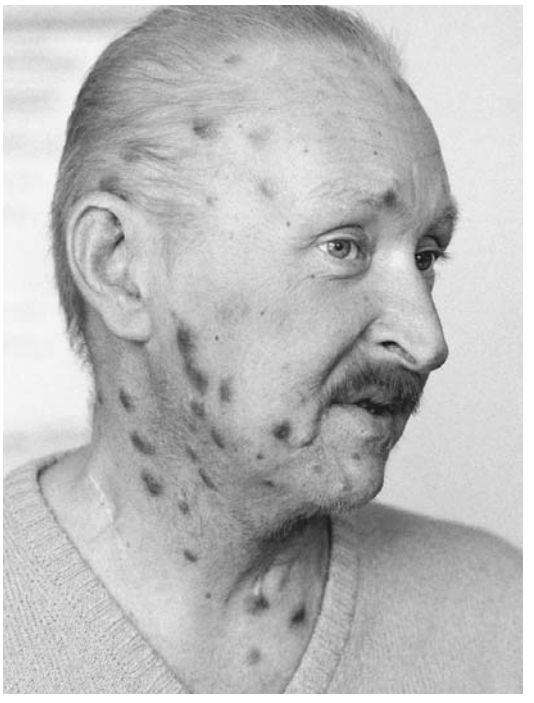
BIRTH OF A KILLER. Believed to have originated in Africa, where the majority of AIDS cases still are found (see Infectious Diseases for statistics on AIDS), the disease first appeared in the United States in 1981. In that year two patients were diagnosed with an unusual form of pneumonia and with Kaposi's sarcoma, a type of cancer that previously had struck only people of Mediterranean origin aged 60 years and older. The appearance of that condition in younger persons of non-Mediterranean origin prompted an investigation by the United States Centers for Disease Control and Prevention (CDC).

Through the efforts of physicians both inside and outside the CDC, understanding of AIDS—the name and acronym appeared in 1982—gradually emerged. In 1983 scientists at

the Pasteur Institute in Paris, as well as a separate team in the United States, identified the virus that causes AIDS, a pathogen that in 1986 was given the name human immunodeficiency virus (HIV). Further research showed that HIV, a retrovirus (see Infectious Diseases for an explanation of retrovirus), is subdivided into two types: HIV-1 and HIV-2. In people who have HIV-2, AIDS seems to take longer to develop; however, neither form of HIV carries with it a guarantee that a person will contract the disease. At first it was believed that if someone were HIV-positive, meaning that the person had the virus, it was a virtual death sentence. Therefore in 1991, when the basketball superstar Earvin "Magic" Johnson (1959–) announced that he was HIV-positive, it was an extremely melancholy event. Fans and admirers all over the world assumed that Johnson shortly would contract AIDS and begin to wither away in the process of suffering an exceedingly panful, dehumanizing death.

The fact that Johnson was alive and healthy more than ten years after the diagnosis of his infection with HIV serves to indicate that there is a great deal of difference between being HIV-positive and having AIDS. It also says much about people's emerging understanding of the disease and the virus that causes it. So, too, does Johnson's experience as he attempted, twice, to make a return to the court after retiring in the wake of his HIV announcement. Before examining his experiences, let us look at the social climate engendered by this politically volatile immunodeficiency syndrome.

CHANGING VIEWS ON AIDS. AIDS first was associated almost exclusively with the male homosexual community, which contracted the disease in large numbers. This had a great deal to do with the fact that male homosexuals were apt to have far more sexual partners than their heterosexual counterparts and because anal intercourse is more likely to involve bleeding and hence penetration of the skin shield that protects the body from infection. The association of AIDS with homosexuality led many who considered themselves part of the societal mainstream to dismiss AIDS as a "gay disease," and the fact that intravenous drug users also contracted the disease seemed only to confirm the prejudice that AIDS had nothing to do with heterosexual non-junkies. Some so-called Christian ministers even went so far as to assert, sometimes with no small amount of satisfaction, that AIDS was God's punishment for homosexuality.



A viral disease that is almost invariably fatal, AIDS destroys the immune systems of its victims, leaving them vulnerable to a variety of illnesses, among them, Kaposi's sarcoma (shown here), a type of cancer that before the 1980s struck only people of Mediterranean origin aged 60 years and older. *(© Roger Ressmeyer/Corbis. Reproduced by*

Then, during the mid-1980s, AIDS began spreading throughout much of society: to heterosexuals, hemophiliacs (see Noninfectious Diseases) and others who received blood, and even babies. The fact that AIDS could be transferred through heterosexual intercourse proved that it was not just a disease of homosexuals. Nor were all homosexuals necessarily susceptible to it. In fact, the safest of all sexual groups was homosexual women, who often tended toward monogamy and whose form of sexual contact was least invasive.

As AIDS spread throughout society, so did paranoia. Rumors circulated that a person could catch the disease from a mosquito bite or from *any* contact with the bodily fluids of another person—not just semen or blood but even sweat or saliva. People with AIDS began to acquire the status lepers once had held (see Infectious Diseases). By the mid-1990s views had changed considerably, and society as a whole had a much more realistic view of AIDS. This came about to

KEY TERMS

ALLERGY: A change in bodily reactivity to an antigen as a result of a first exposure. Allergies bring about an exaggerated reaction to substances or physical states that normally would have little significant effect on a healthy person.

ANTIBODIES: Proteins in the human immune system that help the body fight foreign invaders, especially pathogens and toxins.

ANTIGEN: A substance capable of stimulating an immune response or reaction.

APC: An antigen-presenting cell—a macrophage that has ingested a foreign cell and displays the antigen on its surface.

B CELL: A type of white blood cell that gives rise to antibodies. Also known as a *B lymphocyte.*

EPIDEMIC: Affecting or potentially affecting a large proportion of a population (*adj.*) or an epidemic disease (*n.*)

HUMORAL: Of or relating to the antibodies secreted by B cells that circulate in bodily fluids.

IMMUNE SYSTEM: A network of organs, glands, and tissues that protects the body from foreign substances.

IMMUNITY: The condition of being able to resist a particular disease, particularly through means that prevent the growth and development or counteract the effects of pathogens.

IMMUNOLOGY: The study of the immune system, immunity, and immune responses.

INOCULATION: The prevention of a disease by the introduction to the body, in small quantities, of the virus or other microorganism that causes the disease.

LYMPHOCYTE: A type of white blood cell, varieties of which include B cells and T cells, or B lymphocytes and T lymphocytes.

MACROPHAGE: A type of phagocytic cell derived from monocytes.

MONOCYTE: A type of white blood cell that phagocytizes (engulfs and digests) foreign microorganisms.

MONOGAMOUS: Having only one mate.

PATHOGEN: A disease-carrying parasite, usually a microorganism.

PHAGOCYTE: A cell that engulfs and digests another cell.

T CELL: A type of lymphocyte, also known as a T lymphocyte, that plays a key role in the immune response. T cells include cytotoxic T cells, which destroy virus-infected cells in the cell-mediated immune response; helper T cells, which are key participants in specific immune responses that bind to APCs, activating both the antibody and cell-mediated immune responses; and suppressor T cells, which deactivate T cells and B cells.

VACCINE: A preparation containing microorganisms, usually either weakened or dead, which are administered as a means of increasing immunity to the disease caused by those microorganisms.

some extent because of increased education and awareness—and in no small part because of Johnson, who was by far the most widely known and admired HIV-positive celebrity.

MAGIC COMES BACK. After playing on the United States "Dream Team" that trounced all opponents at the 1992 Summer Olympics in Barcelona, Spain, Johnson attempted a comeback with the Lakers the following year. Owing to fears on the part of many other players that they might contract AIDS by coming into close contact with him on the court, however, he decided again to retire. In December 1991 Johnson had established the Magic Johnson Foundation to promote AIDS awareness, and he devoted himself to this and other AIDS-related causes as well as to other ventures. Raising money for AIDS led him out onto the basketball court again in October 1995, when he and the American All Stars faced an Italian team in a benefit game, with an unsurprisingly lopsided score of 135–81.

Then, in February 1996, Johnson made his second attempted comeback with the Lakers. He ended up retiring again four months later, this time for good, but because he had chosen to and not because he had been forced to do so. Thanks in part to his AIDS education programs, in his second comeback Johnson discovered that players realized that they were not likely to catch the virus on the court. As the New Jersey Nets' player Jayson Williams told one reporter, "You've got a better chance of Ed McMahon knocking on your door with $1 million than you have of catching AIDS in a basketball game."

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THE IMMUNE SYSTEM

CONCEPT

The immune system is a network of organs, glands, and tissues that protects the body from foreign substances. These substances include bacteria, viruses, and other infection-causing parasites and pathogens. Usually, the immune system is extremely effective in performing its work of defending the body, but sometimes an error occurs in this highly complex system, and it can lead to terrible mistakes. The result can be an allergic reaction, which can be as simple as a case of the sniffles and as serious as a fatal condition. Or the error can manifest as an autoimmune disorder, such as lupus, in which the body rejects its own constituents as foreign invaders.

HOW IT WORKS

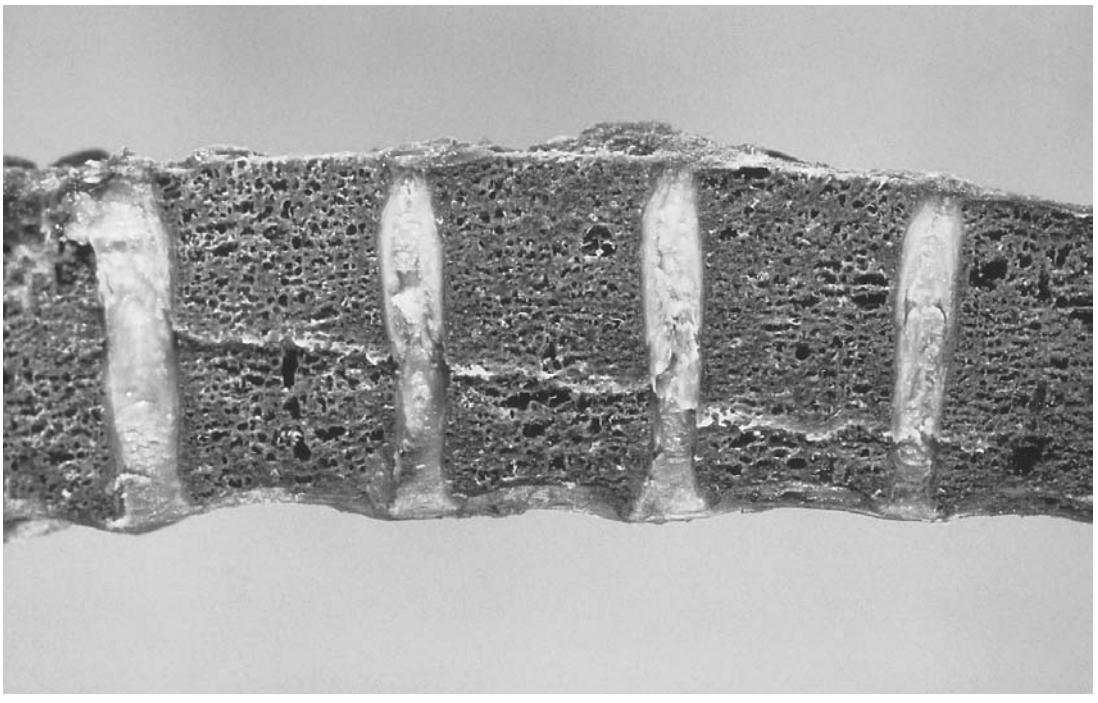
The Immune System in General

The human body is under near constant attack from pathogens, or disease-carrying parasites, of the type discussed in Infection, Infectious Diseases, and Parasites and Parasitology. No human would live very long without the immune system, which includes two levels or layers of protection, the nonspecific and the specific defenses. The nonspecific defenses, including the skin and mucous membranes, serve as a first defensive line for preventing pathogens from entering the body. The specific defenses are activated when these microorganisms get past the nonspecific defenses and invade the body.

For the immune system to work properly, two things must happen: first, the body must recognize that it has been invaded, either by pathogens or toxins or by some other outside threat. Second, the immune response must be activated quickly, before the invaders destroy many body tissue cells. For the immune system to respond effectively, several conditions must be in place, including the proper interaction of nonspecific and specific defenses. The nonspecific defenses on the skin do not identify the antigen (a substance capable of stimulating an immune response or reaction) that is attacking or potentially attacking the body; instead, these defenses simply react to the presence of what it identifies as something foreign. Often, the nonspecific defenses effectively destroy microorganisms, but if these defenses prove ineffective and the microorganisms manage to infect tissues, the specific defenses go into action. The specific defenses function by detecting the antigen in question and mounting a response that targets it for destruction.

THE MAJOR HISTOCOMPATIBILITY COMPLEX. How does the specific system "know" what is foreign and what is part of the body? The cell membrane of every cell is studded with various proteins, which together are known as the major histocompatibility complex, or MHC. The MHC is a kind of pass code, since all cells in the body must possess an identical pattern so that the body will identify those cells as belonging to the "self." An invading microorganism, such as a bacterium, does not have the same MHC, and when the immune system encounters it, it alerts the body that it has been invaded by a foreign cell.

Every person has his or her nearly unique MHC, and the response of the immune system to foreign MHC can pose a problem where organ transplants are concerned. Because the immune



Marrow, the soft tissue at the core of bones, is a key producer both of lymphocytes and of another component of blood, the hemoglobin-containing red blood cells. *(© Lester V. Bergman/Corbis. Reproduced by permission.)*

system interprets the transplanted organ, with its foreign MHC, as an invader, the body may reject the transplant, and therefore organ recipients usually take immunosuppressant drugs to quell the immune response. Furthermore, doctors often attempt transplants only between close relatives, who are likely to have genetically similar MHCs, or try to find organs that match in the major histocompatibility antigens.

Parts of the Immune System

The organs of the immune system include the lymphatic vessels, lymph nodes, tonsils, thymus, Peyer's patch, and spleen. Each of these organs either produces the cells that participate in the immune response or serves as a site for immune function. Lymphocytes, a type of white blood cell, are concentrated in the lymph nodes, which are masses of tissue that act as filters for blood at various places throughout the body-most notably the neck, under the arms, and in the groin. As the lymph (white blood cells plus plasma) filters through the lymph nodes, foreign cells are detected and overpowered.

The tonsils, located at the back of the throat and under the tongue, contain large numbers of lymphocytes and filter out potentially harmful bacteria that might enter the body via the nose and mouth. Peyer's patches, scattered throughout the small intestine and appendix, are lymphatic tissues that perform this same function in the digestive system. The thymus gland, located within the upper chest region, is another site of lymphocyte production, though it is most active during childhood. The thymus gland continues to grow until puberty, protecting a child through the critical years of early development, but in adulthood it shrinks almost to the point of vanishing.

Marrow, the soft tissue at the core of bones, is a key producer both of lymphocytes and of another component of blood, the hemoglobin-containing red blood cells. Because of its critical role in the immune system, it is a very serious decision to allow marrow to be extracted (itself an extremely serious operation, of course) for use in a cancer treatment, as described in Noninfectious Diseases. The spleen, in addition to containing lymphatic tissue and producing lymphocytes, acts as a reservoir for blood and destroys worn-out red blood cells.

Antibodies, B cells, and T cells. The functioning of the immune system also calls into play a wide array of sub-

stances, most notably antibodies and the two significant varieties of lymphocyte: B cells and T cells. Antibodies, the most well known of the three, are proteins in the human immune system that help fight foreign invaders. B cells (B lymphocytes) are a type of white blood cell that gives rise to antibodies, whereas T cells (T lymphocytes), are a type of white blood cell that plays an important role in the immune response. T cells are a key component in the cell-mediated response, the specific immune response that utilizes T cells to neutralize cells that have been infected with viruses and certain bacteria. There are three types of T cells: cytotoxic, helper, and suppressor T cells. Cytotoxic T cells destroy virus-infected cells in the cell-mediated immune response, whereas helper T cells play a part in activating both the antibody and the cell-mediated immune responses. Suppressor T cells deactivate T cells and B cells when needed, and thus prevent the immune response from becoming too intense.

The intricacies of the immune system's functioning are far beyond the scope of this essay. The reader interested in a more in-depth review of the substances, organs, glands, and processes is encouraged to seek clarification from a textbook. On the other hand, a very basic and nontechnical example of how the body resists infection can help clarify, in general terms, how the immune system does its work.

REAL-LIFE APPLICATIONS

Protecting the Body

As discussed in Infection, not all bacteria are bad; in fact, many are helpful or even essential to humans. When the word bacteria is mentioned, however, most of us think of the "bad" bacteria, which is understandable, since there are so many of them and their effects can be so dramatic. Suppose such a bacterium enters the body, which is an easy situation to imagine—it happens all the time. Indeed, even as you are reading these words, literally trillions of bacteria the world over are attempting to invade human bodies, including your own. Their chances of success are determined by the immune system and response.

Most of the time, the skin provides us with sufficient protection from invaders, but if the skin is broken, it creates a pathway for invasion. Even a minor cut on a finger can serve as an opening for a microorganism that, once inside the body, will flourish in the body's warm, blood-washed interior. When it is established, the bacterium begins to divide rapidly, but already the specific immune system has begun to mount its resistance, and sometimes evidence of the battle can be seen on the outside—for example, in the form of a red, pus-exuding welt. In the bloodstream, lymphocytes engulf bacteria and carry them toward the lymph nodes. For this reason, when the body is under attack, it begins producing white blood cells at an accelerated rate, and for this reason doctors sometimes measure a patient's white blood cell count. If the number is high, the physician knows that an infection is active somewhere in the patient's body.

Killer blood cells, known by the generic name phagocyte, engulf the bacteria and digest them, but even as this is occurring, the rapid reproduction of the bacterium provides a challenge to the immune system. If the infectious agent reproduces at a rate beyond the control of the immune system, the physician may provide help in the form of an antibiotic. Alternatively, he or she may lance (cut open) a superficial infection to allow it to drain and to provide access for an antiseptic agent. If the bacterial invasion is minor, the immune system soon dispatches the invader, and the system returns to normal.

Often, some of the white blood cells form antibodies against such invading bacteria, so that the immune system will be better armed to combat any future invasions by the same microorganism. The white blood cell count returns to its normal level, but still with the capability of mobilizing the immune defense on short notice. It is this response that is the basis for inoculations against certain infections, a topic discussed in Immunity. Sometimes, however, something goes wrong in the production of antibodies, and instead of properly protecting the body against invaders, the immune system creates an allergy.

Allergies

An allergy is a change in bodily reactivity to an antigen as a result of a first exposure. Allergies bring about an exaggerated reaction to substances or physical states that would normally have little significant effect on a healthy person. Although the immune system behaves as if it is



Electron micrograph of a single dust mite. Their dead bodies and excrement cause asthma and allergic reactions to household dust. *(© Eye of Science/Photo Researchers. Reproduced by permission.)*

fighting off a pathogen, in fact, it is launching a complex series of reactions against an irritant. The irritant, or allergen, may well be an otherwise innocuous substance that hardly bothers a person without the allergy. It could even be something that other people enjoy—for example, peanuts or bananas—or at least something, such as animal hair, that does not typically cause people undue discomfort. Allergies also may involve a substance, such as venom from a bee sting, that most people consider far from pleasant but which does not pose a serious threat to someone who is not allergic to it.

In extreme cases of allergic reaction, the situation that follows exposure to an allergen truly is one of life and death. The immune response may be accompanied by a number of stressful symptoms, ranging from mild reactions, such as hives (the formation of red, swollen areas on the surface of the skin) to a life-threatening situation known as anaphylactic shock. The latter, a condition characterized by a sudden drop in blood pressure and difficulty in breathing, can be accompanied by acute skin irritation in the form of angry red boils all over the body. Collapse or coma can ensue and may result in death.

CAUSES OF ALLERGY. Pollens from grasses, trees, and weeds produce such allergic reactions as sneezing, runny nose, swollen nasal tissues, headaches, blocked sinuses, and watery, irritated eyes. Of the 46 million allergy sufferers in the United States, about 25 million

KEY TERMS

ALLERGY: A change in bodily reactivity to an antigen as a result of a first exposure. Allergies bring about an exaggerated reaction to substances or physical states that normally would have little significant effect on a healthy person.

ANTIBODIES: Proteins in the human immune system that help fight foreign invaders, especially pathogens and toxins.

ANTIGEN: A substance capable of stimulating an immune response or reaction.

ANTISEPSIS: The practice of inhibiting the growth and multiplication of microorganisms, usually by ensuring the cleanliness of the environment.

APC: An antigen-presenting cell—a macrophage that has ingested a foreign cell and displays the antigen on its surface.

B CELL: A type of white blood cell that gives rise to antibodies. Also known as a *B lymphocyte.*

CELL-MEDIATED RESPONSE: The specific immune response that utilizes T cells to neutralize cells that have been infected with viruses and certain bacteria.

GLAND: A cell or group of cells that filters material from the blood, processes that material, and secretes it either for use again in the body or to be eliminated as waste.

HEMOGLOBIN: An iron-containing protein in red blood cells that is responsible for transporting oxygen to the tissues and removing carbon dioxide from them. Hemoglobin is known for its deep red color.

HUMORAL: Of or relating to the antibodies secreted by B cells that circulate in bodily fluids.

IMMUNE SYSTEM: A network of organs, glands, and tissues that protects the body from foreign substances.

IMMUNITY: The condition of being able to resist a particular disease, particularly through means that prevent the growth and development or counteract the effects of pathogens.

have this form of allergy, known to scientists as rhinitis but to the populace as hay fever. Other common allergens are dust and dust mites, pet hair and fur, insect bites, certain foods or drugs, and skin contact with specific chemical substances. About 12 million Americans are allergic to a variety of chemicals.

Some people are allergic to a wide range of substances, while others are affected by only a few or none. Why the difference? The reasons can be found in the makeup of an individual's immune system, which may produce several chemical agents that cause allergic reactions. The main immune system substances responsible for the symptoms of allergy are the histamines that are produced after exposure to an allergen. When an allergen first enters the body, the lymphocytes make what are known as E antibodies. These antibodies attach to mast cells, large cells that are found in connective tissue and contain histamines. The histamines are chemicals released by basophils, a type of lymphocyte, during the inflammatory response.

The second time a given allergen enters the body of a person who has an allergy, it becomes attached to the E antibodies. They stimulate the mast cells to discharge their histamines and other anti-allergen substances. One type of histamine travels to various receptor sites in the nasal passages, respiratory system, and skin, dilating smaller blood vessels and constricting airways. The results include some of the reactions associ-

KEY TERMS CONTINUED

IMMUNOLOGY: The study of the immune system, immunity, and immune responses.

LYMPH: That portion of the blood that includes white blood cells and plasma but not red blood cells.

LYMPH NODES: Masses of tissue at certain places in the body that act as filters for blood.

LYMPHOCYTE: A type of white blood cell, varieties of which include B cells and T cells, or B lymphocytes and T lymphocytes.

MACROPHAGE: A type of phagocytic cell derived from monocytes.

MHC: Major histocompatibility complex, a group of proteins found on the membrane of each cell in an organism's body. Since all cells in a particular body have the same MHC pattern, the MHC is a kind of pass code, identifying cells in the body as belonging to the "self."

MONOCYTE: A type of white blood cell that phagocytizes (engulfs and digests) foreign microorganisms.

PATHOGEN: A disease-carrying parasite, usually a microorganism.

PHAGOCYTE: A cell that engulfs and digests another cell.

T CELL: A type of white blood cell, also known as a *T lymphocyte,* that plays a key role in the immune response. T cells include cytotoxic T cells, which destroy virus-infected cells in the cell-mediated immune response; helper T cells, which are key participants in specific immune responses that bind to APCs, activating both the antibody and cell-mediated immune responses; and suppressor T cells, which deactivate T cells and B cells.

TISSUE: A group of cells, along with the substances that join them, which form part of the structural materials in plants or animals.

WHITE BLOOD CELLS: Blood cells that are colorless, lack hemoglobin, have a nucleus, and include the lymphocytes and other varieties.

ated with allergies, for instance, sneezing or the formation of hives. Another type of histamine constricts the larger blood vessels and travels to the receptor sites found in the salivary and tear glands and in the stomach's mucosal lining. These histamines stimulate the release of stomach acid, thus creating a stomach ulcer condition.

TREATMENTS. There are many treatments for allergy, including (obviously) avoidance of the substance to which the patient is allergic. Among these treatments are the administration of antihistamines, which either inhibit the production of histamine or block histamines at receptor sites. After the administration of antihistamines, E antibody receptor sites on the mast cells are blocked, thereby preventing the release of the histamines that cause the allergic reactions. The allergens are still there, but the body's allergic reactions are suspended for the period of time that the antihistamines are active. Antihistamines, sold both in prescription and over-the-counter forms, also constrict the smaller blood vessels and capillaries, thereby removing excess fluids. Decongestants can bring relief as well, but they can be used for only a short time, since their continued use can irritate and intensify the allergic reaction.

In cases of extreme allergic reaction leading to anaphylactic shock, the patient may require an injection of epinephrine (also sometimes called *adrenaline*), a hormone that the body produces for responding to situations of fear and danger.

In the case of anaphylactic shock, which involves such severe constriction of the breathing passages that the patient runs a risk of suffocation, epinephrine causes the passages to open, making it possible to breathe again. It also constricts the blood vessels, increasing the pressure and making the blood move more rapidly throughout the body. The body's own supply of epinephrine is not enough to counteract anaphylactic shock, however, and therefore a person experiencing that condition must receive an emergency injection containing many times the amount of the hormone naturally supplied by the body. It may be administered at a hospital, though doctors usually advise people with severe allergies to keep an emergency supply on hand.

Autoimmune Disorders

Allergies are one example of an immune system gone awry, and though they can be fatal, they typically are a reaction to only one or two substances. An autoimmune disorder, on the other hand, is an entirely different class of phenomenon: it a condition in which a person's body actually rejects itself. This condition comes about when the ability of the immune system to read MHCs becomes scrambled, such that it fails to recognize cells from within the body and instead rejects them as though they came from outside. As a result, the body sets in motion the same destructive operation against its own cells that it normally would carry out against bacteria, viruses, and other such harmful invaders.

The reasons why the immune system becomes dysfunctional are not well understood, but most researchers agree that a combination of genetic, environmental, and hormonal factors plays into autoimmunity. They also speculate that certain mechanisms may trigger it. First, a substance normally restricted to one part of the body, and therefore not usually exposed to the immune system, is released into other areas, where it is attacked. Second, the immune system may mistake a component of the body for a similar foreign component. Third, cells of the body may be altered in some way, by drugs, infection, or some other environmental factor, so that they are no longer recognizable as "self" to the immune system. Fourth, the immune system itself may be dysfunctional, for instance, because of a genetic mutation.

Some autoimmune diseases. Examples of autoimmune disorders include lupus, rheumatoid arthritis, autoimmune hemolytic anemia, pernicious anemia, and type 1 diabetes mellitus. (The last of these diseases is discussed in Noninfectious Diseases.) Lupus, or systemic lupus erythematosus, is seen mainly in young and middle-aged women, and its symptoms include fever, chills, fatigue, weight loss, skin rashes (especially a "butterfly" rash on the face), patchy hair loss, sores in the mouth or nose, enlargement of the lymph nodes, stomach problems, and irregular menstrual cycles. Lupus also may induce problems in the cardiopulmonary, urinary, and central nervous systems and can cause seizures, depression, and psychosis.

Rheumatoid arthritis, as its name suggests, is a type of both rheumatism and arthritis, which are general names for diseases associated with inflammation of connective tissue. Rheumatoid arthritis occurs when the immune system attacks and destroys the tissues that line bone joints and cartilage. The disease can affect any part of the body, although some joints may be more susceptible than others are. As it progresses, joint function diminishes sharply, and deformities arise.

Like rheumatism and arthritis, anemia is a general term for several conditions. Forms of it are marked either by a lack of red blood cells (hemoglobin) or by a shortage in total blood volume, and these deficiencies can produce effects that range from lethargy or sluggishness to death. Autoimmune hemolytic anemia occurs when the body makes antibodies that coat red blood cells. Patients have been known to experience a variety of symptoms, including jaundice, characterized by a yellowish coloration, before dying—sometimes just a few weeks after showing the first signs of the disease.

Pernicious anemia was so named at a time when it, too, was almost always fatal (*pernicious* means "deadly"), though treatments developed in the twentieth century have changed that situation. A disorder in which the immune system attacks the lining of the stomach in such a way that the body cannot metabolize vitamin B_{12} (see Vitamins), pernicious anemia manifests symptoms that include weakness, sore tongue, bleeding gums, and tingling in the extremities. Because the disease leads to a decrease in stomach acid, nausea, vomiting, loss of appetite, weight loss, diarrhea, and constipation are also

possible. Furthermore, since B_{12} is essential to the functioning of the nervous system, a deficiency can result in a host of neurological problems, including weakness, lack of coordination, blurred vision, loss of fine motor skills, impaired sense of taste, ringing in the ears, and loss of bladder control.

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INFECTION

PARASITES AND PARASITOLOGY

INFECTION

PARASITES AND PARASITOLOGY

CONCEPT

When people hear the word *parasite,* one of the first ideas or images that probably comes to mind is that of disease. Though many parasites do carry diseases, including some extremely deadly ones, "disease-carrying" is not necessarily a defining characteristic of a parasite. Rather, a parasite can be identified as any organism that depends on another organism, the host, for food, shelter, or some other benefit and which receives these benefits in such a way that the host experiences detrimental effects as a consequence. Theoretically, organisms from all across the kingdoms of living things can be characterized as parasites; in practice, however, the realm of organisms studied by parasitologists is confined to protozoa and various species within the animal kingdom, mostly worms and arthropods. Included among these organisms are countless varieties of tapeworm and roundworm as well as a parade of insects that have plagued humankind since the dawn of time: cockroaches, lice, bedbugs, flies, fleas, ticks, mites, and mosquitoes.

HOW IT WORKS

Symbiosis

Parasitism belongs within the context of symbiosis, a term for a biological relationship in which two species live in close proximity to each other and interact regularly in such a way as to benefit one or both of the organisms. In addition to the symbiosis of two species (that is, at least two individuals representing two different species), it is also possible for a symbiotic relationship to exist between two organisms of the same species. Organisms engaging in symbiotic relationships are called *symbionts.*

There are three basic types of symbiosis, differentiated as to how the benefits (and the detriments, if any) are distributed. In the case of parasitism, of course, the arrangement benefits only one of the two: the parasite, an organism that obtains nourishment or other life support at the expense of the host. Though predation (the relationship of predator to prey) is technically a form of symbiosis, it usually is not considered in the context of symbiotic relationships; therefore, parasitism is really the only variety of symbiosis that is detrimental to one of the organisms. Unlike the predator killing its prey, however, the parasite allows its host to live as long as possible, since it depends on the host for support and sustenance.

A second type of symbiosis, commensalism, likewise involves a benefit to only one of the two organisms, but in commensalism the beneficiary, or commensal, manages to receive its benefits without causing any detriment to the host. The other variety of symbiosis is mutualism, an arrangement from which both partners receive benefits. (Commensalism and mutualism, along with the overall concept of symbiosis, are discussed at much greater length in Symbiosis.)

In addition to the distinctions among parasitism, commensalism, and mutualism, symbiotic relationships are distinguished according to the participants' ability to live without each other. In a facultative relationship, the partners can live apart successfully, whereas in an obligate one, the interacting species are incapable of living separately. Needless to say, for most parasites the relationship is obligate, whereas from the

host's viewpoint, the arrangement is more than facultative: not only *could* the host live without the parasite, but it actually would be better off without the tiny hanger-on.

Defining the Limits of Parasitology

The realm of parasitism and parasitic creatures is far larger and more varied than that of parasitology. In other words, the range of organisms that exhibit parasitic behavior is much greater than the variety of species that are considered within the realm of parasitological study. Among the parasitic species excluded from ordinary parasitology are two named in the title of a book in the bibliography at the end of this essay: *Despicable Species: On Cowbirds, Kudzu, Hornworms, and Other Scourges,* by Janet Lembke.

The cowbird is a species that exploits the instinctive tendency of other birds to care for their young. Rather than raise its offspring, it leaves its eggs with other birds, which mistake the eggs for their own and provide them with food and care. Meanwhile, the adult cowbird goes on about its business, freed from the responsibility of raising its own progeny. (See Instinct and Learning for more on this subject.)

Kudzu is a plant that grows at an amazing rate, covering hillsides and virtually every surface to which it can attach itself. During the 1930s agricultural officials in the American South advocated the planting of kudzu, imported from China, as a means of controlling erosion on hillsides. The plant did help control erosion, but it virtually took over parts of Georgia, Alabama, Mississippi, and neighboring states. Only through successful, or at least partially successful, eradication campaigns did county and state governments, as well as private landowners, manage to stem the tide of kudzu's onslaught.

Cowbirds are clearly parasitic in their behavior, and kudzu is unquestionably a pest in plant form (i.e., a weed), but this does not truly make them parasites in the sense that parasitologists use the term. Nor, as we noted earlier, does the capacity to cause or carry disease necessarily define a parasite, though many parasites (known collectively as pathogens) do carry diseases. And even though many species of viruses, bacteria, and fungi exhibit parasitic behavior and can be transmitted by parasites, scientists usually study them separately in the context of infectious diseases.

Protozoa, worms, and arthropods. After making all the exclusions indicated in the foregoing paragraph, the species studied within the realm of parasitology are only those creatures within certain phyla from two kingdoms: animals and protists. The latter category, which includes algae (other than blue-green algae), slime molds, and protozoa, is made up primarily of unicellular, eukaryotic organisms. (A eukaryote is a cell that has a nucleus, as well as organelles, or sections of the cell that perform specific functions, enclosed in membranes.)

Among protists, of principal concern is protozoa, which, unlike other protists, are capable of moving on their own. All the species we discuss in the remainder of this essay fall into one of three general categories: protozoa, worms, and arthropods, the latter two being groups of creatures within the animal kingdom.

The Taxonomy of Worms and Arthropods

Taxonomy, or the area of the biological sciences devoted to the classification of species, is an exceedingly complex area of study. Within that realm, there are numerous matters that either are or have been areas of dispute, among them the classification of protozoa as protists rather than animals. Owing to differences between taxonomic systems and the complications involved in explaining the characteristics that unify members of particular phyla (the next-largest major taxonomic ranking after kingdom), we will dispense with any effort to delineate classifications of species rigorously.

In other words, we will take a much simpler approach, a fact signaled by the use of the very general word *worm.* Whereas arthropods are a genuine phylum whose characteristics we examine shortly, *worms* is simply a broad term that encompasses numerous phyla: Platyhelminthes (flatworms), Nemertea (or Rhynchocoela, ribbon worms), Acanthocephala (spiny-headed worms), Aschelminthes, Priapulida (priapulids), and Annelida (annelid worms).

The classification of the many species of worm serves to illustrate just how complex a subject taxonomy can be. The group Aschelminthes, for example, is divided into five classes—Rotifera, Gastrotricha, Kinorhyncha, Nematoda, and Nematomorpha—that sometimes are treated as separate phyla. Yet another classification system

groups the worms into phyla completely different from the ones named here. Therefore, rather than hopelessly confusing the issue, in the present context we will call them all simply *worms* and not attempt to map the complex relationships between the species that fall under that heading.

ARTHROPODS. In contrast to worms, arthropods, or members of the phylum Arthropoda, are much easier to identify. Arthropoda is the largest phylum in the animal kingdom, accounting for some 84% of all known animal species. Nearly 900,000 arthropod species have been identified, the vast majority of them being insects, but some zoologists maintain that this number represents but a tiny fraction of all species within this enormous phylum. In fact, there may be as many as ten million species of insect alone.

Arthropods are identified by a nonliving exoskeleton (an external skeleton), by segmented bodies, and by jointed appendages in pairs. The four subphyla of phylum Arthropoda are Trilobita, Crustacea, Chelicerata, and Uniramia. The first of these subphyla became extinct during the "Great Dying" that marked the end of the Permian period some 245 million years ago. (See Paleontology for more on this subject.) The second includes numerous organisms that humans eat, such as crabs and shrimp, as well as a few parasitic species. The most familiar parasites, however, belong to the other two subphyla. Within Chelicerata, by far the largest class is Arachnida, whose name might be familiar from that of the 1990 horror film about spiders, *Arachnophobia.* In addition to spiders, Arachnida includes scorpions, ticks, and mites, among which are many parasitic creatures.

Finally, there is subphylum Uniramia, which includes several classes, such as Chilopoda and Diplopoda (centipedes and millipedes, respectively); the largest class is unquestionably Insecta. In the latter group are some of the most obnoxious creatures known, including the genera *Anopheles* (mosquitoes), *Glossina* (tsetse fly), and *Climex* (bedbugs) as well as the species *Periplaneta americana* (American cockroach), *Phthirus pubis* (pubic or crab louse), and *Tunga penetrans* (sand flea).

Parasite Homes and Life Cycles

Most insects are ectoparasites, or parasites that live outside a host's body, whereas protozoa and worms are endoparasites, or parasites that live inside a host's body. As we shall see, insects are often vectors, or organisms that transmit pathogens, meaning that they serve as a delivery vehicle for the disease-causing protozoa and worms. Because endoparasites interact with the bodies of their hosts in much more complex ways, we devote more space to those species.

In general, the life cycle of most worms begins in the body of a definitive host, a host that provides a setting for the sexual reproduction of parasites. (For most of the parasites we consider, humans are the definitive host.) The parasite's eggs pass from the body of the definitive host, usually through the feces, and hatch in an inorganic medium, typically water. From there, the parasites enter the body of either a vector or an intermediate host. The latter is defined by the fact that sexual reproduction of parasites does not take place in its body; for the parasites to reproduce sexually, they must enter the body of a definitive host, where the cycle begins again. There may be more than one intermediate host, and they are identified, respectively, as first intermediate host, second intermediate host, and so on.

For protozoa the life cycle is much as we have described; however, the concept of a definitive host, as we have defined it, does not usually enter in, since protozoa reproduce asexually. Nonetheless, they typically begin life in the intestinal tracts or other organs of a host, pass through the feces into the water supply, and enter the body either of a vector or a new host.

REAL-LIFE APPLICATIONS

Protozoa

They may be single-cell organisms, compared with the many millions of cells that make up the vastly more complex human body, but protozoa have been the cause of more human suffering and death than almost any category of disease-carrying organism. Intestinal protozoa are common throughout the world, particularly in areas where food and water sources are subject to contamination from animal and human waste. Like soldiers sneaking into a city disguised as civilians, protozoa typically enter the body while still in an inactive state, thus getting around any defenses the immune system might put up against them.

Protozoa in this inactive state, encased in a protective outer membrane, are known as cysts. As cysts, they enter the gastrointestinal tract of the host before developing into a mature form that feeds and reproduces.

Other types of parasitic protozoa infect the blood or tissues of their hosts. These protozoa typically enter the host through a vector. Often the vector is an invertebrate (an animal without an internal skeleton), such as an insect, that feeds on the host and passes the protozoan on through the bite wound. The effects that protozoan parasites can have on human bodies range from no symptoms to extreme ones. Some victims of *Trichomonas vaginalis,* known colloquially as trick, are asymptomatic, meaning that they show no obvious symptoms of their condition. It is an STD, or sexually transmitted disease, for which men are typically carriers, passing it on to female sexual partners. Males do exhibit some symptoms, but usually it is the female who experiences the worst symptoms of the infection, including a burning sensation when urinating, genital itching, and a white discharge. When such pain is not present, the disease can be detected only by finding the trophozoites (protozoa in a feeding stage, as opposed to a reproductive or resting stage) in secretions within the victim's genital tract.

INTESTINAL PROTOZOA. A classic intestinal protozoan is *Giardia lamblia.* Like all unicellular organisms, it is extremely small, with a length of about 15 microns, or micrometers, equal to about 0.00059 in. It has a teardrop shape with two nuclei on either side of a rod called an axostyle, and under a scanning electron microscope the nuclei look like eyes separated by a nose. For this reason, people who have glimpsed *G. lamblia* under such magnification have reported the decidedly unsettling sensation of a microorganism "staring back at them."

These protozoa carry a condition known as *giardiasis.* As cysts, they pass through the feces of one host and enter the body of the next through contaminated food or water. The resulting symptoms can range from nothing to severe diarrhea. Not surprisingly, giardiasis is fairly common in developing countries, where open sewers commonly run through the city streets. Also, there are places in the third world where farmers use human feces as a fertilizer, another significant source of infection. Yet giardiasis is not simply an affliction of people in developing nations; rather, the ease with which the pathogen can contaminate water supplies makes it a condition known the world over. Even in the United States and other industrialized nations, *G. lamblia* may find its way into water supplies when waste-disposal systems are placed too close to wells. Campers who unwisely drink water from mountain streams also may contract giardiasis, which may come from beavers—hence the nickname "beaver fever," which is sometimes given to giardiasis contracted in the wild.

Far more notorious and destructive is *Entamoeba histolytica,* carrier of amoebic dysentery. The process of infection is much the same as with *G. lamblia,* but once *E. histolytica* enters the host's body, it can wreak considerably more damage. In most cases, the parasite causes only diarrhea and relatively minor gastrointestinal problems, but it can bring about a rupture of the gastrointestinal tract (the stomach and intestines). Trophozoites may even pass into the circulatory system or other organs, such as the liver, and amoebic dysentery can be fatal.

BLOOD INFECTIONS. Among the most significant protozoan blood infections is African trypanosomiasis, or "sleeping sickness." The parasite enters humans through the bite of the tsetse fly, a bloodsucking pest that serves as vector for the *Trypanosoma* genus of parasites. The result is fever, inflammation of the lymph nodes (masses of tissue at certain places in the body that filter blood), and various negative effects on the brain and spinal cord that bring about extreme lethargy or tiredness—hence the name. Sleeping sickness, prevalent throughout central Africa, is frequently fatal.

Still worse is the disease carried by the *Plasmodium* genera: malaria, which has been described at the leading health problem in the world today. It is estimated that more than two billion people live in regions where malaria is endemic (native), that the number of persons infected may be as high at 750 million, and that as many as three million people die of the disease each year. Four species of *Plasmodium,* borne by mosquitoes, are capable of infecting humans and causing malaria. *P. falciparum* is the most dangerous of the four strains; it can kill a healthy adult in 48 hours.

Inside the human host, the parasite finds a home in the red blood cells, where it reproduces until the cell bursts, spreading more parasites

throughout the blood. These new parasites infect and destroy more red blood cells. As a new generation of parasites bursts from the blood cells, the body tries to defend itself by causing a fever, which does destroy many (but not all) of the pathogens. Scientists have developed several chemical antidotes to malaria; unfortunately, strains of pathogen resistant to these antidotes are on the rise in various parts of the world.

Worms

The protozoa we have discussed up to this point, as well as the conditions that they carry, are far from pleasant. But the many species we examine under the general heading of "worms" are vastly more disgusting, if that is to be believed. It should be stated that much of what follows is not for those of weak stomach and probably should not be read while eating.

In contrast to protozoa, worms are relatively complex, large creatures with fairly long life spans. For example, the genera *Schistosoma*, or blood flukes, average 0.4 in. (10 mm) in length, while *Clonorchis sinensis* (Chinese, or oriental, liver fluke) may attain lengths of about 1 in. (25 mm). Additionally, they can live for very long spans of time: a blood fluke (fluke is simply a more common way of designating a nematode, a type of worm) may last as long as 30 years.

During that time, a female blood fluke can produce several hundred eggs *a day.* Blood flukes are one of the few worm species in which the sexes are separate; most worms are hermaphrodites, or both male and female. This brings up another distinction between worms and protozoa: the fact of sexual reproduction. From this follows yet another distinction, the involvement (typically) of one or more intermediate hosts as well as a definitive host, in whose body sexual reproduction takes place.

Flukes and other worms can be as destructive as many of their protozoan counterparts. Blood flukes, for instance, kill some one million people a year by inflaming tissues and causing organs, including the liver and small intestine, to cease functioning. Oriental liver flukes, so named because they are common throughout eastern Asia, pass through the bodies of snails (first intermediate host) to fish (second intermediate host) and ultimately to humans (definitive host), who are infected by eating raw or undercooked fish. They block the bile ducts in the liver, a condition that can be fatal.



Flukes and other worms can be as destructive as many of their protozoan counterparts; oriental liver flukes, for example, pass through the bodies of snails to fish and then to humans, who are infected by eating raw or undercooked fish. They block the bile ducts in the liver, a condition that can be fatal. *(Photo Researchers. Reproduced by permission.)*

Tapeworms and the dangers of undercooked meat. There are numerous species of tapeworm, which may be as long as 50 ft. (15 m). Their bodies are made up of segments called proglottids, which contain male and female sexual organs and which house their eggs. Proglottids break off, usually into the feces of the host, thus enabling the spread of the tapeworm. One variety, *Dipylidium caninum* (cucumber tapeworm), uses dogs or cats as a definitive host, entering the body when the animal ingests a flea or louse, which serves as an intermediate host. Several varieties of worm can enter the body through improperly cooked pork. This is a testament to the wisdom of the injunctions against eating pork in the Old Testament and Koran, which were written for peoples in a world without refrigeration or sophisticated medical knowledge.



Found in central Africa and parts of Asia, Wuchereria bancrofti is carried by mosquitoes and causes a condition known as elephantiasis. This parasite makes its way to the lymph nodes and brings about grotesque swelling. *(© Sheldan Collins/Corbis. Reproduced by permission.)*

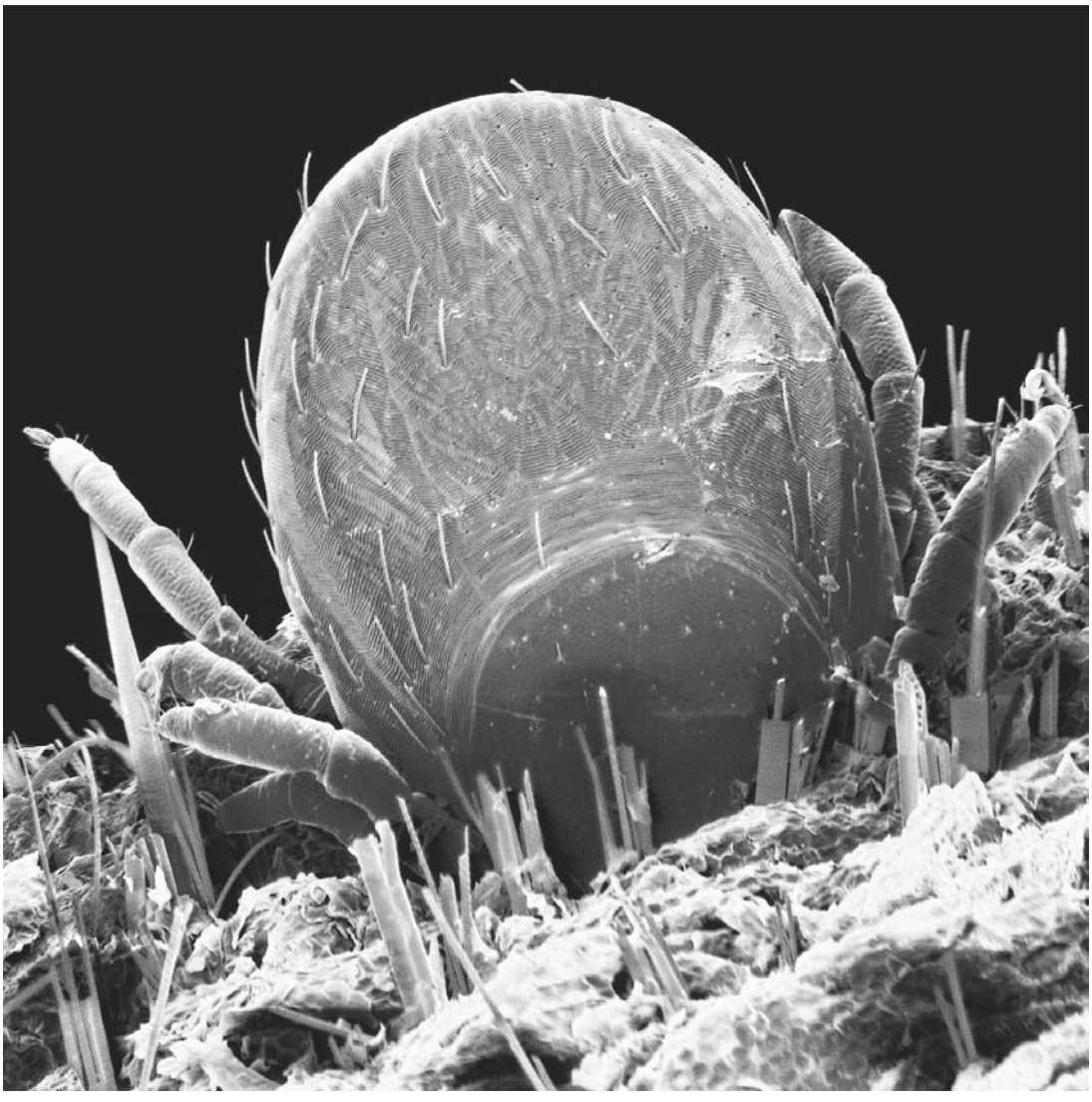
The *Taenia* genus of tapeworm includes *T. solium,* the pork tapeworm, which has been known to crawl out of the anus of an infected human. Another worm often found in undercooked pork is *Trichinella spiralis,* which brings about the condition known as trichinosis. The latter disease is rarely fatal, but it can cause extreme discomfort, characterized by sore, tender muscles. Thanks to enhanced efforts at meat inspection, the incidence of trichinosis in U.S. pigs has dropped to less than 1%. Nonetheless, it is still quite possible to ingest the parasite from eating undercooked game, particularly bear.

WORMS THAT AFFLICT LARGE POPULATIONS. Hookworms such as *Necator americanus* afflict more than a billion people as well as untold numbers of dogs and cats. In fact, one of the ways that the parasites spread is through human exposure to dog and cat feces. Some hookworms can produce as many as 25,000 eggs a day, wreaking havoc on the host, on whose blood the hookworms depend for sustenance. As its name implies, *N. americanus* is found in the New World, and was a widespread affliction throughout the southeastern United States during the early part of the twentieth century. Another common species, *Ancylostoma duodenale,* is found in southern Europe, northern Africa, northern Asia, and parts of South America.

Pinworms, carriers of a condition known as enterobiasis, are also common in the United States, and in much of the world as a whole. They primarily afflict preschool and school-age children who live in crowded conditions, though adults can often contract enterobiasis as well. Pinworms infect about half as many people as hookworms, but the effects can be extremely painful, especially because they are felt in the perianal skin, or the skin around the anus, and (for adult women) in the genitals. The eggs hatch on the perianal skin, which causes it to itch, but if the victim scratches the area, this can cause additional bacterial infections. The affliction of pinworms can be especially severe for children, who often experience irritability, insomnia, restlessness, and other behavioral changes. They are highly contagious and can contaminate nonliving surfaces such as bed linens and carpets; therefore, if one family member is infected, the whole family usually must receive treatment. Drugs for treating pinworm are sold either as prescription or over-the-counter drugs, and treatment usually involves two doses over the course of two weeks.

Ascaris lumbricoides, or intestinal roundworms, may infect as much as one-fourth of the world's population. Affected areas are mostly in the third world, though in the United States, an estimated 10,000 cases of roundworm infection—frequent in dogs and cats—occur in humans. The roundworm pathogen goes through a strange life cycle inside the human body, hatching in the small intestine and making its way into the air passages, only to be swallowed and returned to the small intestine. It can cause a fluid buildup in the lungs, resulting in what is known as *ascaris pneumonia,* an often fatal disease. As with *T. solium,* the intestinal roundworm has been known to escape the body, though in an even more shocking way. Because it is very sensitive to anesthetics, the parasite may evacuate the body of a patient in a surgical recovery room by moving from the small intestine to the stomach and out the nose or mouth.

OTHER WORMS. Several other worms have been associated with various dis-



Scanning electron micrograph of a tick feeding in human skin. A tick is a parasitic arthropod that can serve as a vector for bacterial infections, such as Rocky Mountain spotted fever. *(Photo Researchers. Reproduced by permission.)*

eases in parts of the third world. Among them are *Loa loa,* or the "eye worm," found primarily in equatorial Africa. These worms live just under the skin and, as their name indicates, just under the surface of the eyeball. *Onchocerca volvulus,* also common in Africa as well as Arabia and Latin America, afflicts an estimated 30 million people. When it enters the human eye, it dies, eventually bringing about blindness. Because the vector, a black fly, breeds in rivers, the disease is commonly called *river blindness,* and in some towns it has blinded as much as 40% of the adult population.

Found in central Africa and parts of Asia, *Wuchereria bancrofti* is carried by mosquitoes and causes a condition known as *elephantiasis.* The parasite makes its way to the lymph nodes, particularly those that drain lower parts of the body, and brings about grotesque swelling, usually in the legs and genitals. (Visitors to the "Parasites and Parasitological Resources" Web site of Ohio State University's College of Biological Sciences, will find links to photographs of elephantiasis victims. It should be noted that these images include grotesquely swollen male genitalia and may be too graphic for some viewers.)

Arthropods

After the preceding discussion of worms, mere insects and other arthropods probably will

KEY TERMS

ARTHROPOD: A term for members of the phylum Arthropoda, largest in the animal kingdom. Arthropods are identified by a nonliving exoskeleton (an external skeleton), by segmented bodies, and by jointed appendages that appear in pairs. Among the classes within this phylum are Arachnida (spiders, scorpions, ticks, and mites) and Insecta.

ASYMPTOMATIC: Displaying no symptoms of a disease or other condition.

CLASS: The third-largest major, or obligatory, taxonomic classification rank, smaller than *phylum* but larger than *order.*

COMMENSALISM: A symbiotic relationship in which one organism, the commensal, benefits without causing any detriment to the other organism, the host.

CYST: A protozoan in an inactive state, encased in a protective outer membrane. Protozoa usually enter the bodies of hosts in the form of cysts.

DEFINITIVE HOST: The host in whose body a parasite reproduces sexually. A parasite enters a definitive host either through a vector, an intermediate host, or through some other source, such as a water supply.

ECTOPARASITES: Parasites that live outside a host's body.

ENDOPARASITES: Parasites that live inside a host's body.

EUKARYOTE: A cell that has a nucleus, as well as organelles (sections of the cell that perform specific functions) that are bound by membranes.

FACULTATIVE: A term for a symbiotic relationship in which partners are capable of living apart.

GASTROINTESTINAL TRACT: The stomach and intestines.

GENUS: The second-smallest major taxonomic classification rank, smaller than *family* and larger than *species.*

HOST: The term for an organism that provides a benefit or benefits to another organism in a symbiotic relationship of commensalism or parasitism. See also *intermediate host* and *definitive host.*

INTERMEDIATE HOST: A creature that serves as host to a parasite, which it receives either directly (typically through the water supply) or from a vector before passing it on to a definitive host. Parasites do not reproduce sexually inside an intermediate host.

LYMPH NODES: Masses of tissue at certain places in the body that act as filters for blood.

not have the same power to disgust the reader as they otherwise might have had. This is particularly so because most arthropods are ectoparasites, and not as many of them are associated with diseases. This is not to say that arthropod parasites are anything pleasant or that they could be described as upstanding citizens of the biological world—only that, compared with worms, they are not quite so revolting.

Certainly many insect parasites, such as mosquitoes (genus *Anopheles*), are notorious vectors. Of the 400 or so mosquito species, about a dozen carry malaria, and many others transmit canine heartworm. Some parasites are known as *mechanical,* as opposed to biological, vectors. This means that they may happen to carry cysts of protozoa, or worm eggs, on their exteriors, but they do not serve as the biological carrier of any

KEY TERMS CONTINUED

OBLIGATIVE: A term for a symbiotic relationship in which the partners, if they were separated, would be incapable of continuing to live.

PARASITE: A general term for any organism that depends on another organism for support, which it receives at the expense of the other organism.

PARASITISM: A symbiotic relationship in which one organism, the parasite, benefits at the expense of the other organism, the host.

PARASITOLOGY: A biological discipline devoted to the study of parasites but primarily those among the animal and protist kingdoms. Parasitic bacteria, fungi, and viruses usually are studied within the context of infectious diseases.

PATHOGEN: A disease-carrying parasite, typically a microorganism.

PHYLUM: The second-largest major taxonomic classification rank, smaller than *kingdom* but larger than *class.*

PROTISTS: A term for members of the kingdom Protista, which includes algae (other than blue-green algae, which are monerans), slime molds (a group of about 500 species that resemble fungi), and protozoa.

PROTOZOAN: A term that refers to some 50,000 species of mobile protists.

SUBPHYLUM: A classification rank, smaller than that of phylum but larger than that of class, that is sometimes used to indicate a level between those two major ranks.

SYMBIOSIS: A biological relationship in which (usually) two species live in close proximity to each other and interact regularly in such a way as to benefit one or both of the organisms. Symbiosis may exist between two or more individuals of the same species as well as between two or more individuals representing two different species. The three principal varieties of symbiosis are *mutualism, commensalism,* and *parasitism.*

TAXONOMY: The area of the biological sciences devoted to the classification of organisms according to apparent common characteristics.

TROPHOZOITE: A protozoan in a feeding stage, as opposed to a reproductive or resting stage.

VECTOR: An organism, such as an insect, that transmits a pathogen to the body of a host.

disease. Such is the case with the American cockroach (*Periplaneta americana*). But one thing unites all insect parasites: they are pests, and if any of their species ever became endangered (something that is not likely to happen), very few people would be upset.

ARTHROPODS THAT CAUSE ITCHING. The bedbug (genus *Cimex*) is an insect parasite that is not known to serve as a vector, either mechanical or biological, for any disease—yet it certainly gives rise to more than its share of misery. Like many another arthropod parasite, it causes its hosts to itch. Most familiar from the old saying "don't let the bedbugs bite," bedbugs live not only in beds but also in clothing, furniture, laundry, and numerous other areas around a house. And though they depend on human blood, it does no good simply to vacate a house for a few days in the hope of starving

them; they can survive for up to year on the blood supplies they have stored in their bodies.

Then there are body lice (*Pediculus humanus*) and pubic, or crab, lice (*Phthirus pubis*). Although people may tend to associate the problem of lice with the poor, lice afflict all socioeconomic classes. Body lice, as their name indicates, spread all over the body and particularly the head, while crab lice nest either in the pubic area or anywhere else they can find short, thick hair: armpits, eyebrows, eyelashes, beards, sideburns, and mustaches. Other than inducing itching, most lice do not pose a serious threat—unless they happen to be carrying typhus or other diseases.

Other insect parasites known to cause itching are cat and dog fleas (*Ctenocephalides felis* and *C. canis,* respectively), which may carry the cucumber tapeworm we discussed earlier. Sand fleas (*Tunga penetrans*) are not associated with any disease, but by causing hosts to scratch, they can bring about secondary infections, and they become so firmly attached to the host that they usually require surgical removal.

Like the insects we have described, most arachnid parasites also produce itching. Among these parasites are several varieties of tick, which can serve as vectors for bacterial infections, such as Rocky Mountain spotted fever. Tick species such as *Ixodes dammini* in the northeastern United States carry Lyme disease, named after the town in Connecticut were it was first identified in 1975. Effects of Lyme disease can range from itching to severe neurological disorders. There are also several varieties of mange mites, among them *Sarcoptes scabiei,* which afflicts humans and animals with scabies, characterized by severe skin inflammation and itching.

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INFECTION

CONCEPT

Humans may hold dominance over most other life-forms on Earth, but a few varieties of organism have long held mastery over us. Ironically, these life-forms, including bacteria and viruses, are so small that they cannot be seen, and this, in fact, has contributed to their disproportionate influence in human history. For thousands of years, people attributed infection to spiritual causes or, at the very least, to imbalances of "humors," or fluids, in the human body. Today germ theory and antisepsis—the ideas that microbes cause infection and that a clean body and environment can prevent infections—are ingrained so deeply that we almost take them for granted. Yet these concepts are very recent in origin, and for a much longer span of human history people quite literally wallowed in filth—with predictable consequences.

HOW IT WORKS

What Is Infection?

The term infection refers to a state in which parasitic organisms attach themselves to the body, or to the inside of the body, of another organism, causing contamination and disease in the host organism. Parasite refers generally to any organism that lives at the expense of another organism, on which it depends for support. Numerous parasites and the diseases they cause are discussed in the essay Parasites and Parasitology; in the present context, we are concerned primarily with infections that relate to bacteria and viruses.

Almost all infections contracted by humans are passed along by other humans or animals. Infections fall into two general categories: exogenous, or those that originate outside the body, and endogenous, which occur when the body's resistance is lowered. Examples of exogenous infection include catching a cold by drinking after someone else from the same glass; coming down with salmonella after ingesting undercooked eggs, meat, or poultry; getting rabies from a dog bite; or contracting syphilis, AIDS (acquired immunodeficiency syndrome), or some other sexually transmitted disease from an infected partner.

Any number of factors—lack of sleep, prolonged exposure to extreme cold or moisture, and so on—can lower the body's resistance, opening the way for an endogenous infection. Malnutrition, illness, and trauma also can be factors in endogenous infection. Substance abuse, whether it be the use of tobacco in its many forms, excessive drinking, or drug use, lowers the body's resistance. Furthermore, all of these behaviors tend to be coupled with poor eating habits, which invite infection by denying the body the nutrients it needs.

Some Terms

A whole array of terminology attends the study of infection and infectious diseases, a subject that is touched upon in the present context but explored at length in its own essay as well. Among these terms are the names for the different branches of study relating to infection, its agents, and the resulting diseases. Although germ theory is a term (defined later) that is used widely in the context of infection, *germ* itself—a common word in everyday life—is not used as much as microorganism or pathogen. The latter word

refers to disease-carrying parasites, which are usually microorganisms. Two of the principal types of pathogen, bacteria and viruses, are discussed later in this essay.

Words relating to the effects of infectious agents include *epidemic,* an adjective meaning "affecting or potentially affecting a large proportion of a population"; as a noun, the word refers to an epidemic disease. *Pandemic* also doubles as an adjective, meaning "affecting an extremely high proportion of a population over a wide geographic area," and a noun, referring to a disease of pandemic proportions. Areas of study relating to pathogens, their effects, and the prevention of those effects include the following.

- Bacteriology: An area of the biological sciences concerned with bacteria, including their importance in medicine, industry, and agriculture
- Epidemiology: An area of the medical sciences devoted to the study of disease, including its incidence, distribution, and control within a population
- Etiology: A branch of medical study concerned with the causes and origins of disease. Also, a general term referring to all the causes of a particular disease or condition
- Immunology: The study of the immune system, immunity, and immune responses
- Pathology: The study of the essential nature of diseases
- Virology: The study of viruses

In addition, there are several terms relating to the prevention of infection.

- Antibiotic: A substance produced by, or derived from, a microorganism, which in diluted form is capable of killing or at least inhibiting the action of another microorganism. Antibiotics typically are not effective against viruses.
- Antisepsis: The practice of inhibiting the growth and multiplication of microorganisms
- Germ theory: A theory in medicine, widely accepted today, that infections, contagious diseases, and other conditions are caused by the actions of microorganisms
- Immunity: A condition of being able to resist a particular disease, particularly through means that prevent the growth and development of pathogens or counteract their effects
- Inoculation: The prevention of a disease by the introduction to the body, in small quantities, of the virus or other microorganism that causes the disease
- Vaccine: A preparation containing microorganisms, usually either weakened or dead, which are administered as a means of increasing immunity to the disease caused by those microorganisms

Some of these words appear in this essay and others in related essays on infectious diseases and immunity.

BACTERIA

Five major groups of microorganisms are responsible for the majority of infections. They include protozoa and helminths, or worms—both of which are considered in Parasites and Parasitology—as well as bacteria and viruses. Bacteria and viruses often are discussed, along with fungi (the fifth major group), in the context of infection and infectious diseases. In the present context, however, we limit our inquiry to viruses and bacteria.

Bacteria are very small organisms, typically consisting of one cell. They are prokaryotes, a term referring to a type of cell that has no nucleus. In eukaryotic cells, such as those of plants and animals, the nucleus controls the cell's functions and contains its genes. Genes carry deoxyribonucleic acid (DNA), which determines the characteristics that are passed on from one generation to the next. The genetic material of bacteria is contained instead within a single, circular chain of DNA.

Members of kingdom Monera, which also includes blue-green algae (see Taxonomy), bacteria generally are classified into three groups based on their shape: spherical (coccus), rodlike (bacillus), or spiral- or corkscrew-shaped (spirochete). Some bacteria also have a shape like that of a comma and are known as *vibrio.* Spirochetes, which are linked to such diseases as syphilis, sometimes are considered a separate type of creature; hence, Monera occasionally is defined as consisting of blue-green algae, bacteria, *and* spirochetes.

The cytoplasm (material in the cell interior) of all bacteria is enclosed within a cell membrane that itself is surrounded by a rigid cell wall. Bacteria produce a thick, jellylike material on the surface of the cell wall, and when that material

forms a distinct outer layer, it is known as a capsule. Many rod, spiral, and comma-shaped bacteria have whiplike limbs, known as flagella, attached to the outside of their cells. They use these flagella for movement by waving them back and forth. Other bacteria move simply by wiggling the whole cell back and forth, whereas still others are unable to move at all.

Bacteria most commonly reproduce by fission, the process by which a single cell divides to produce two new cells. The process of fission may take anywhere from 15 minutes to 16 hours, depending on the type of bacterium. Several factors influence the rate at which bacterial growth occurs, the most important being moisture, temperature, and pH, or the relative acidity or alkalinity of the substance in which they are placed.

Bacterial preferences in all of these areas vary: for example, there are bacteria that live in hydrothermal vents, or cracks in the ocean floor, where the temperature is about 660°F (350°C), and some species survive at a pH more severe than that of battery acid. Most bacteria, however, favor temperatures close to that of the human body—98.6°F (37°C)—and pH levels only slightly more or less acidic than water. Since they are composed primarily of water, they thrive in a moist environment.

Viruses

One of the interesting things about bacteria is their simplicity, coupled with the extraordinary complexity of their interactions with other organisms. As simple as bacteria are, however, viruses are vastly more simple. Furthermore, the diseases they can cause in other organisms are at least as complex as those of bacteria, and usually much more difficult to defeat. Whereas there are "good" bacteria, as we shall see, scientists have yet to discover a virus whose impact on the world of living things is beneficial. There is something downright creepy about viruses, which are not exactly classifiable as living things; in fact, a virus is really nothing more than a core of either DNA or RNA (ribonucleic acid), surrounded by a shell of protein.

Two facts separate viruses from the world of the truly living. First, unlike all living things (even bacteria), viruses are not composed of even a single cell, and, second, a virus has no life if it cannot infect a host cell. When we say "no life" in this context, we truly mean *no life.* Although parasites, including bacteria and those species discussed in Parasites and Parasitology, depend on other organisms to serve as hosts, they can live when they are between hosts. They are rather like a person between jobs: without other means of support, the person eventually will go broke or starve, but typically such a person can hang on for a few months until he or she finds a new job. A virus without a host, on the other hand, is simply not alive—not dead, like a formerly living thing, but more like a machine that has been switched off.

Once a virus enters the body of a host, it switches on, and the result is truly terrifying. In order to produce new copies of itself, a virus must use the host cell's reproductive "machinery"—that is, the DNA. The newly made viruses then leave the host cell, sometimes killing it in the process, and proceed to infect other cells within the organism. As for the organisms that viruses target, their potential victims include the whole world of living things: plants, animals, *and* bacteria. Viruses that affect bacteria are called bacteriophages, or simply phages. Phages are of special importance, because they have been studied much more thoroughly than most viruses; in fact, much of what virologists now know about viruses is based on the study of phages.

REAL-LIFE APPLICATIONS

Bacteria and Humans

Not all bacteria are harmful; in fact, some even are involved in the production of foods consumed by humans. For example, bacteria that cause milk to become sour are used in making cottage cheese, buttermilk, and yogurt. Vinegar and sauerkraut also are produced by the action of bacteria on ethyl alcohol and cabbage, respectively. Other bacteria, most notably *Escherichia coli* (*E. coli*) in the human intestines, make it possible for animals to digest foods and even form vitamins in the course of their work. (See Digestion for more on these subjects.) Others function as decomposers (see Food Webs), aiding in the chemical breakdown of organic materials, while still others help keep the world a cleaner place by consuming waste materials, such as feces.

Despite its helpful role in the body, certain strains of *E. coli* are dangerous pathogens that

can cause diarrhea, bloody stools, and severe abdominal cramping and pain. The affliction is rarely fatal, though in late 1992 and 1993 four people died during the course of an *E. coli* outbreak in Washington, Idaho, California, and Nevada. More often the outcome is severe illness that may bring on other conditions; for example, two teenagers among a group of 11 who became sick while attending a Texas cheerleading camp had to receive emergency appendectomies. The pathogen is usually transmitted through undercooked foods, and sometimes through other means; for example, a small outbreak in the Atlanta area in the late 1990s occurred in a recreational water park.

BACTERIAL INFECTIONS. Many bacteria attack the skin, eyes, ears, and various systems in the body, including the nervous, cardiovascular, respiratory, digestive, and genitourinary (i.e., reproductive and urinary) systems. The skin is the body's first line of defense against infection by bacteria and other microorganisms, although it supports enormous numbers of bacteria itself. Bacteria play a major role in a skin condition that is the bane of many a young man's (and, less frequently, a young woman's) existence: acne. Pimples or "zits," known scientifically as *Acne vulgaris,* constitute one of about 50 varieties of acne, or skin inflammation, which are caused by a combination of heredity, hormones, and bacteria—particularly a species known as *Propionibacterium acnes.* When a hair follicle becomes plugged by sebum, a fatty substance secreted by the sebaceous, or oil, glands, this forms what we know as a blackhead; a pimple, on the other hand, results when a bacterial infection, brought about by *P. acnes,* inflames the blackhead and turns it red. For this reason, antibiotics may sometimes cure acne or at least alleviate the worst symptoms.

Acne may seem like a life-and-death issue to a teenager, but it goes away eventually. On the other hand, toxic shock syndrome (TSS), caused by other bacteria at the surface of the skin—species of *Staphylococcus* and *Streptococcus*—can be extremely dangerous. The early stages of TSS are characterized by flulike symptoms, such as sudden fever, fatigue, diarrhea, and dizziness, but in a matter of a few hours or days the blood pressure drops dangerously, and a sunburn-like rash forms on the body. Circulatory problems arise as a result of low blood pressure, and some extremities, such as the fingers and toes, are deprived of blood as the body tries to shunt blood to vital organs. If the syndrome is severe enough, gangrene may develop in the fingers and toes.

In 1980, several women in the United States died from TSS, and several others were diagnosed with the condition. As researchers discovered, all of them had been menstruating and using high-absorbency tampons. It appears that such tampons provide an environment in which TSS-causing bacteria can grow, and this led to recommendations that women use lower-absorbency tampons if possible, and change them every two to four hours. Since these guidelines were instituted, the incidence of toxic shock has dropped significantly, to between 1 and 17 cases per 100,000 menstruating women.

Many bacteria produce toxins, poisonous substances that have effects in specific areas of the body. An example is *Clostridium tetani,* responsible for the disease known as *tetanus,* in which one's muscles become paralyzed. A related bacterium, *C. botulinum,* releases a toxin that causes the most severe form of food poisoning, botulism. Salmonella poisoning comes from another genus, *Salmonella,* which includes *S. typhi,* the cause of typhoid fever.

Viral Infections

With viruses, as we have noted, there is no need even to discuss "good" kinds, because there is no such thing—*all* viruses are harmful, and most are killers. The particular strains of virus that attack animals have introduced the world to a variety of ailments, ranging from the common cold to AIDS and some types of cancer. Other diseases related to viral infections are hepatitis, chicken pox, smallpox, polio, measles, and rabies.

One reason why physicians and scientists have never found a cure for the common cold is that it can be caused by any one of about 200 viruses, including rhinoviruses, adenoviruses, influenza viruses, parainfluenza viruses, syncytial viruses, echoviruses, and coxsackie viruses. Each has its own characteristics, its favored method of transmission, and its own developmental period. These viruses can be transmitted from one person to another by sneezing on the person, shaking hands, or handling an object previously touched by the infected person. Surprisingly, some more direct forms of contact with an infected person, as in kissing, seldom spread viruses.

A group of viruses called the *orthomyxoviruses* transmit influenza, an illness usually characterized by fever, muscle aches, fatigue, and upper respiratory obstruction and inflammation. The most common complication of influenza is pneumonia, a disease of the lungs that may be viral or bacterial. The viral form of pneumonia that goes hand in hand with influenza can be very severe, with a high mortality (death) rate; by contrast, bacterial pneumonia, which typically appears five to ten days after the onset of flu, can be treated with antibiotics.

THE EVER ELUSIVE VIRUS. Viruses are tricky. Because their generations are very short and their structures extremely simple, they are constantly mutating (altering their DNA and hence their heritable traits) and thus becoming less susceptible to vaccines. This is the reason why flu vaccine has to be prepared anew each year to target the current strains, and even then the vaccine is far less than universally effective. On the other hand, vaccination has a high rate of success for strains of virus that undergo little mutation—for example, the smallpox virus.

One particularly elusive type of virus is known as a *retrovirus,* which reverses the normal process by which living organisms produce proteins. Ordinarily, DNA in the cell's nucleus carries directions for the production of new protein. Coded messages in the DNA molecules are copied into RNA molecules, which direct the manufacture of new protein. In retroviruses, that process is reversed, with viral RNA used to make new viral DNA, which then is incorporated into host cell DNA, where it is used to direct the manufacture of new viral protein. Among the diseases caused by retroviruses is AIDS, discussed in Infectious Diseases and The Immune System.

Fighting the Invisible War

Every day of our lives, we are at war with microorganisms, both individually and as a species. It is a war that has lasted for several million years, with billions of lives in the balance, yet it is an invisible war. Up until a few centuries ago, in fact, we had no idea what we were fighting. Before the advent of germ theory, the most scientific theories of disease blamed them either on an imbalance of "humors" (blood, phlegm, yellow bile, and green bile), or on inhaling bad air. These were the most advanced ideas, the ones held by men of learning; most of the populace, by contrast, believed that disease was caused by evil spirits, cast upon individuals or populations by an angry God as punishment for disobedience.



TWO CHILDREN ARE CONFINED TO IRON LUNGS AS THE RESULT OF INFECTION WITH POLIOVIRUS; SIX OF THE CHILDREN IN THIS ONE FAMILY WERE STRICKEN WITH THE VIRUS. AN EPIDEMIC DISEASE CAN AFFECT A LARGE PROPORTION OF A POPULATION, AS HAPPENED IN THE CASE OF POLIO IN THE MIDDLE OF THE TWENTIETH CENTURY. *(© Bettmann/Corbis. Reproduced by permission.)*

Personal hygiene and public health were completely foreign concepts: not only did people bathe infrequently, but they also thought nothing of throwing trash—including rotting food and even human excrement—into the city streets. This image of trash in the streets may call to mind a city of medieval Western Europe, a place and time widely known for its filth, squalor, and ignorance. Yet such an image also describes Athens during the fifth century B.C., when human imagination, wisdom, and appreciation for beauty reached perhaps their highest points in all of history. In the Athens of Socrates, Herodotus, Hippocrates, and Sophocles, the streets were piled with trash and crawling with vermin. In fact, this lack of concern for cleanliness contributed directly to the end of the Greek golden age, sometimes known as the Age of Pericles, after Athens's great leader (495–425 B.C.)—who died in a great plague that swept the germ-ridden city.



ANTON VAN LEEUWENHOEK'S PROTOTYPE MICROSCOPE. THE INVENTION OF THE MICROSCOPE MADE IT POSSIBLE TO SEE BACTERIA AND OTHER MICROORGANISMS, WHICH VAN LEEUWENHOEK, THE FIRST HUMAN BEING TO OBSERVE THEM, DUBBED ANIMALCULES, OR "TINY ANIMALS." *(© Bettmann/Corbis. Reproduced by permission.)*

BACTERIOLOGY AND ANTISEPSIS. The first inkling of any etiology other than that of imbalanced humors and demons was the work of the Italian physician Girolamo Fracastoro (*ca.* 1483–1553), who put forth the theory that disease is caused by particles so small they are almost imperceptible. The invention of the microscope in 1590 made it possible to glimpse those particles, which Holland's Anton van Leeuwenhoek (1632–1723)—the first human being to observe bacteria and other microorganisms—dubbed *animalcules,* or "tiny animals." The German scholar Athanasius Kircher (1601–1680) also observed "tiny worms" in the blood and pus of plague victims and theorized that they were the source of the infection. This was the first theory that dealt with microbial agents as infectious organisms.

In 1848 Ignaz P. Semmelweis (1818–1865), a Hungarian physician working in German hospitals, came up with a novel idea: after examining the bodies of women who had died of puerperal (childbed) fever, he suggested that doctors should wash their hands in a solution of chlorinated lime water before touching a pregnant patient. Semmelweis's idea resulted in a drastic reduction of puerperal fever cases, but his colleagues denounced his outlandish notion as a useless and foolish waste of time. Six years later, in 1854, modern epidemiology was born when the English physician John Snow (1813–1858) determined that the source of a cholera epidemic in London could be traced to the contaminated water of the Broad Street pump. After he ordered the pump closed, the epidemic ebbed—and still many physicians refused to believe that invisible organisms could spread disease.

GERM THEORY. A major turning point came just three years later, in 1857, when the great French chemist and microbiologist Louis Pasteur (1822–1895) discovered that heating beer and wine to a certain temperature killed bacteria that caused these liquids to spoil or turn into vinegar. Thus was born the process of pasteurization, still used today to purify such foods as milk, because, as Pasteur observed, "There are similarities between the diseases of animals or man and the diseases of beer and wine." Pasteur also dealt the final blow to spontaneous generation, a centuries-old belief that living organisms could originate from nonliving matter. As he showed in 1861, microorganisms present in the air can contaminate solutions that seem sterile.

Then, in 1876, the German physician Robert Koch (1843–1910) proved what Kircher had postulated two centuries earlier: that bacteria can cause diseases. Koch showed that the bacterium *Bacillus anthracis* was the source of anthrax in cattle and sheep and generalized the methodology he had used in that situation to form a specific set of guidelines for determining the cause of infectious diseases. Known as Koch's postulates, these guidelines define a truly infectious agent as one that can be isolated from an infected animal, cultured in a laboratory setting, introduced into a healthy animal to produce the same infection as in the first animal, and isolated again from the second animal. These ideas formed the basis of research into bacterial diseases and are still dominant in the sciences devoted to the study of disease.

Koch's postulates helped usher in what has been called the golden era of medical bacteriology. Between 1879 and 1889 German microbiologists isolated the organisms that cause cholera, typhoid fever, diphtheria, pneumonia, tetanus, meningitis, and gonorrhea as well the *Staphylococcus* and *Streptococcus* organisms. Even as

KEY TERMS

ANTIBIOTIC: A substance produced by or derived from a microorganism, which in diluted form is capable of killing or at least inhibiting the action of another microorganism. Antibiotics are not usually effective against viruses.

ANTISEPSIS: The practice of inhibiting the growth and multiplication of microorganisms, generally by ensuring the cleanliness of the environment.

BACTERIOLOGY: An area of the biological sciences concerned with bacteria, including their importance in medicine, industry, and agriculture.

DNA: Deoxyribonucleic acid, a molecule in all cells, and many viruses, containing genetic codes for inheritance.

ENDOGENOUS: A term for an infection that occurs when the body's resistance is lowered. Compare with *exogenous.*

EPIDEMIC: Affecting or potentially affecting a large proportion of a population (*adj.*) or an epidemic disease (*n.*)

EPIDEMIOLOGY: An area of the medical sciences devoted to the study of disease, including its incidence, distribution, and control within a population.

ETIOLOGY: A branch of medical study concerned with the causes and origins of disease; also, a general term referring to all the causes of a particular disease or condition.

EXOGENOUS: A term for an infection that originates outside the body. Compare with *endogenous.*

GENE: A unit of information about a particular heritable (capable of being inherited) trait that is passed from parent to offspring, stored in DNA molecules called *chromosomes.*

GERM THEORY: A theory in medicine, widely accepted today, that infections, contagious diseases, and other conditions are caused by the actions of microorganisms.

IMMUNITY: The condition of being able to resist a particular disease, particularly through means that prevent the growth and development of pathogens or counteract their effects.

IMMUNOLOGY: The study of the immune system, immunity, and immune responses.

INFECTION: A state or condition in which parasitic organisms attach themselves to the body or to the inside of the body of another organism, producing contamination and disease in the host.

INOCULATION: The prevention of a disease by the introduction to the body, in small quantities, of the virus or other microorganism that causes the disease.

MUTATION: Alteration in the physical structure of an organism's DNA, resulting in a genetic change that can be inherited.

PANDEMIC: Affecting an extremely high proportion of a population over a wide geographic area (*adj.*) or a disease of pandemic proportions (*n.*)

PARASITE: A general term for any organism that depends on another organism for support, which it receives at the expense of the other organism.

PARASITOLOGY: A biological discipline devoted to the study of parasites, primarily those among the animal and protist

KEY TERMS CONTINUED

kingdoms. Parasitic bacteria, fungi, and viruses usually are studied within the context of infectious diseases.

PATHOGEN: A disease-carrying parasite, typically a microorganism.

PATHOLOGY: The study of the essential nature of diseases.

PUBLIC HEALTH: A set of policies and methods for protecting and improving the health of a community through efforts that include disease prevention, health education, and sanitation.

RNA: Ribonucleic acid, the molecule translated from DNA in the cell nucleus, the control center of the cell, that directs protein synthesis in the cytoplasm, or the space between cells.

VACCINE: A preparation containing microorganisms, usually either weakened or dead, which is administered as a means of increasing immunity to the disease caused by those microorganisms.

VECTOR: An organism, such as an insect, that transmits a pathogen to the body of a host.

Koch's work was influencing the development of the germ theory, the influence of the English physician Joseph Lister (1827–1912) was being felt in operating rooms. Building on the work of both Semmelweis and Pasteur, Lister—for whom the well-known antiseptic mouthwash Listerine was named—began soaking surgical dressings in carbolic acid, or phenol, to prevent postoperative infection.

ANTIBIOTICS. Whereas antisepsis was the great battleground of the invisible war during the nineteenth century, in the twentieth century the most important struggle concerned the development of antibiotics. The first effective medications to fight bacterial infection in humans were sulfa drugs, developed in the 1930s. They work by blocking the growth and multiplication of bacteria and were initially effective against a broad range of bacteria, but many strains of bacteria have evolved resistance to them. Today, sulfa drugs are used most commonly in the treatment of urinary tract infections and for preventing infection of burn wounds.

The importance of sulfa drugs was eclipsed by that of penicillin, first discovered in 1928 by the British bacteriologist Alexander Fleming (1881–1955). Working in his laboratory, Fleming noticed that a mold that had fallen accidentally into a bacterial culture killed the bacteria. Having identified the mold as the fungus *Penicillium notatum,* Fleming made a juice with it that he called penicillin. He administered it to laboratory mice and discovered that it killed bacteria in the mice without harming healthy body cells.

It would be more than a decade before the development of a form of penicillin that could be synthesized easily. This drug arrived on the scene in 1941—just in time for the years of heaviest fighting in World War II—and after the war pharmaceutical companies began to manufacture numerous varieties of antibiotic. By the last decade of the twentieth century, however, a new problem emerged: bacteria were becoming resistant to antibiotics. This has been the case with medications used to treat conditions ranging from children's ear infections to tuberculosis.

An example is amoxicillin, a penicillin derivative developed in the late twentieth century. Many pediatricians found it a better treatment than penicillin for ear infections, because it did not tend to cause allergic reactions sometimes associated with the other antibiotic. However, by the late 1990s evidence surfaced indicating that certain types of bacteria had developed a protein that rendered amoxicillin ineffective against ear infections. Critics of amoxicillin (or of antibiotic treatments in general) maintained that widespread prescription of the antibiotic actually helped create that situation, because the bacteria developed the protein mutation defensively.

Because of these and similar concerns associated with antibiotics, doctors have begun taking measures toward controlling the spread of antibiotic-resistant diseases, for instance by prescribing antibiotics only when absolutely necessary. Research into newer types and combinations of drugs is ongoing, as is research regarding the development of vaccines to prevent bacterial infections.

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BRAIN AND BODY

CHEMORECEPTION

BIOLOGICAL RHYTHMS

CHEMORECEPTION

CONCEPT

Chemoreception is a physiological process whereby organisms respond to chemical stimuli. Humans and most higher animals have two principal classes of chemoreceptors: taste (gustatory receptors), and smell (olfactory receptors). Though our sense of smell assists us in distinguishing among tastes, the gustatory and olfactory receptors are different in many respects—not only in their locations but also in terms of their chemical and neurological makeup. Capabilities of taste and smell vary widely among people, as a function of genetics, age, and even personal habits. Likewise, culture influences attitudes toward taste and smell. As for the animal kingdom, certain creatures are gifted with exceedingly acute senses, particularly where smell is concerned, but for some invertebrates, such as worms, there is really little distinction between taste and smell. Among the most interesting aspects of chemoreception in animals is the use of smell for communication, particularly through the release of special chemicals called pheromones. As to whether pheromones, which function as sex attractants, play a role in human interaction, many scientists remain skeptical.

HOW IT WORKS

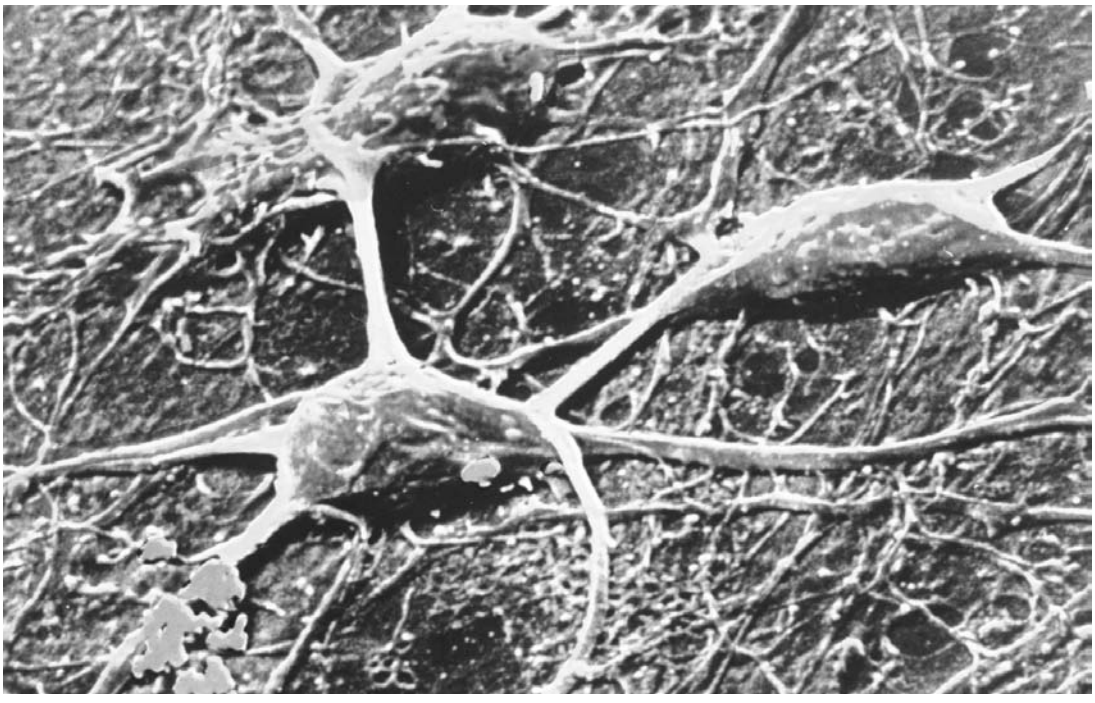
The Senses

The term *sense,* which also may be called sensory reception and sensory perception, refers to the means by which an organism (usually an animal) receives signals regarding physical or chemical changes or both in its environment. Sensory reception and perception entail the translation of these signals, which represent changes in the matter or energy of the environment, into processes within the body and brain. For example, if you eat a cookie, your sense of taste translates the chemical data from that cookie into the sensation of sweetness, a sensation your brain most likely perceives as a pleasing one.

In everyday language, people are accustomed to speaking of five senses possessed by humans and, to a greater or lesser degree, by other animals: sight, touch, smell, hearing, and taste. The reality is rather more complex. For one thing, there are not really just five senses; rather, there are at least five others—and there may be more, depending on just how one defines and classifies the senses. These other senses include the kinesthetic sense, or the discernment of motion; the sensation of temperature, or distinguishing relative heat and cold; the awareness of pressure; the sense of equilibrium or balance; and the perception of pain.

All of these senses involve a response to stimuli, which may be defined as any phenomenon (that is, an observable fact or event, such as an environmental change) that directly influences the activity or growth of a living organism. Each of these senses has a biological component as well as a physical or a chemical one. In the next few paragraphs, we briefly discuss what this means, first by considering the nervous system in general terms and then by looking at the physical and chemical receptors that transmit data through that system.

THE NERVOUS SYSTEM. All sensation is biological in the sense that an organism not only must be living to experience it but also must have a functioning nervous system. The latter is a network, found in the bodies of all verte-



CHEMORECEPTION IS THE MEANS BY WHICH AN ORGANISM RECEIVES SIGNALS REGARDING CHEMICAL CHANGES IN ITS ENVIRONMENT, TRANSLATING THEM INTO PROCESSES WITHIN THE BODY AND BRAIN. NERVE CELLS, SUCH AS THE ONES SHOWN HERE, MAKE UP A NETWORK OF PRIMARY RECEPTORS THAT RECEIVE AND INTERPRET STIMULI AND TRANSMIT MESSAGES BASED ON THESE SENSORY DATA TO THE BRAIN. *(Photograph by Secchi-Lecague/Roussel-UCLAF/CNRI/Science Photo Library. National Audubon Society Collection/Photo Researchers, Inc. Reproduced by permission.)*

brates (animals with internal skeletons), whose purpose is to receive and interpret stimuli and to transmit impulses. Parts of the nervous system include the brain, spinal cord, nerves, and other components.

To be experienced through the senses, all data must be transmitted to the brain through the nervous system. This happens through the conversion and transmission of physical or chemical information, which takes place in sensory nerves known as receptors. A receptor is a structure in the nervous system that receives specific stimuli and is affected in such a way that it sends particular messages to the brain. The brain interprets these messages as sensations corresponding to the stimuli. Primary receptors are those that directly convert stimuli to electronic signals, which they send to the brain. Neurons, or nerve cells, serve as primary receptors. In addition, there are secondary receptors, which simply transmit signals between neurons. Secondary receptors induce a response in an adjoining neuron, thus sending the signal down the line toward the brain.

PHYSICAL AND CHEMICAL RECEPTORS. As we have noted, the changes in the outside environment that the brain interprets as sensation are either physical or chemical in origin. By *physical,* we mean the types of data and phenomena that are studied in the science of physics: matter, energy, and the interactions between them. Likewise, *chemical,* refers to objects of study in the scientific realm of chemistry: elements, compounds, and mixtures.

In the human body there are sensory nerves devoted to the interpretation of physical or chemical data. Among the receptors of physical data are photoreceptors, which respond to light and therefore play a part in the sense of sight; thermoreceptors, which respond to temperature and are concerned with the sense of heat and cold; and nociceptors, or pain receptors. In addition, there are mechanoreceptors, which respond to the mechanical properties of matter and are involved in the senses of touch, hearing, and equilibrium.

As for chemical data, they are interpreted through chemoreceptors, which govern the senses of smell and touch. For this reason, chemore-

ceptors sometimes are referred to as the chemical senses. Our focus in the present context, of course, is on *chemoreception,* the term for the physical process whereby organisms—not just humans, but virtually all animals—respond to chemical stimuli.

DISTINGUISHING GUSTATION AND OLFACTION

We tend to associate taste and smell, and indeed there is some relation between them, but there are also numerous distinctions. Not everyone with an acute sense of smell, for instance, has as finely honed a sense of taste. Conversely, people with poor senses of smell do not necessarily suffer a corresponding impairment in their taste buds. The neurological structures that have to do with taste and smell, at least in higher animals, are not the same. Whereas gustatory sensation travels via secondary receptors called epithelial cells, which pass messages to adjacent neurons, olfactory signals enter the nervous system through primary receptors.

The principal sensory organs of gustation and olfaction in a human being are, respectively, the taste buds on the tongue and the olfactory receptors located within the olfactory epithelium in the nasal cavity. They are designed to respond to two entirely different types of chemical materials. Taste buds are best at receiving sensory data from water-soluble chemicals, or those that dissolve in water, while the olfactory receptors are most attuned to vapors that are water-insoluble.

WATER AND OIL. Almost everyone who has ever eaten a hot, spicy dish has tried to "put out the fire" in their mouths by drinking water, only to discover to their dismay that water only seemed to make the problem worse. On the other hand, milk is usually quite effective. The reason is that most spicy-hot substances tend to be oily, and therefore they do not readily form intermolecular bonds with water. On the other hand, milk, though it is largely composed of water, also contains oily fat particles. Thanks to the chemistry of water- and oil-based substances, it is true (as the old saying goes) that "oil and water don't mix."

In water, hydrogen and oxygen have significantly different levels of electronegativity, or the relative ability of an atom to attract valence electrons, which are used in chemical bonding. Therefore, a water molecule tends to be electrically bipolar, with all the negative charges on the end or side where the oxygen atom is located and all the positive charges on the end or side of the hydrogen molecules. In petroleum and most other oily substances, however, the molecules typically include some combination of carbon and hydrogen, which have similar electronegativity values. For that reason, the electric charges are distributed more or less evenly throughout the molecule. As a result, oily substances form very loose intermolecular bonds, and they tend not to bond with water-based substances.

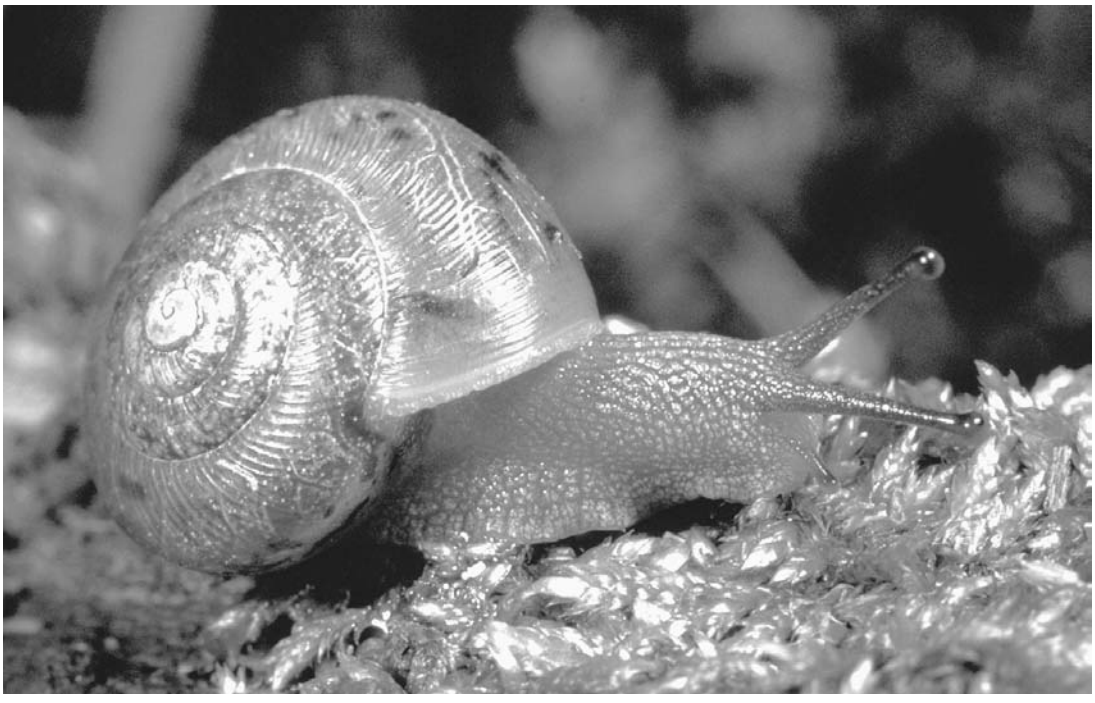
As for taste buds and olfactory membranes, it is fitting that the taste buds would be more receptive to water-based foods and liquids, since most foods (including jalapeño peppers) contain at least some water. Obviously, if we can taste spicy-hot substances, then there must be some receptivity to oil-based foods. Part of this receptivity involves the olfactory membranes, which, as we have noted, are more receptive to oily materials.

ANIMALS AND CHEMORECEPTION

Just as taste and smell are sharply distinguished in humans (despite the fact that smell aids us in the process of tasting), the same is true of most vertebrates. In the case of invertebrates, such as worms, however, there is much less differentiation between gustatory and olfactory receptors. These animals, in fact, may have only one chemical sense, with only slight differences between what scientists call distance chemoreception, more or less the same as smell in vertebrates, and contact chemoreception, which corresponds to vertebrates' sense of taste.

Such analogies can be made because distance chemoreceptors appear to respond to non-water-soluble substances in the same way that the olfactory receptors in vertebrates do, while contact chemoreceptors are more responsive to water-soluble chemicals. As with many other animals, these senses are linked to numerous behaviors—not just feeding—in invertebrates. Distance chemoreception enables invertebrates to sense the presence of chemicals that pose a danger, signaling the need to move away, while contact chemoreception assists the invertebrate in determining when to mate and when to lay eggs.

THE MANY FUNCTIONS OF CHEMORECEPTION. Terrestrial, or land-based, animals whose skins secrete mucus



Terrestrial animals whose skins secrete mucus, like the snail, have what scientists call the common chemical sense, which makes them sensitive to the presence of foreign chemicals on the surface of their bodies. *(JLM Visuals. Reproduced by permission.)*

(e.g., snails and slugs) as well as aquatic animals have what scientists call the *common chemical sense,* which makes them sensitive to the presence of foreign chemicals anywhere on the surface of their bodies. Even humans and other animals whose skin does not secrete mucus across its entire surface have an evolutionary remnant of this sense. Thus, the mucous membranes in the eyes, mouth, nose, and genitals respond to chemical irritants.

This is yet another example of the fact that, while chemoreception in animals is associated most readily with tasting and smelling, it is linked to myriad other functions as well. Some insects may use chemoreception to detect the presence of moisture, and many animals apply it for a variety of purposes. Such purposes include selection and courtship of a mate as well as the identification of friends or foes. A dogs' sense of smell tells it everything it needs to know about a new animal or person it encounters; similarly, a cat may identify another cat by sniffing its rectum. Smell also can be used to mark territory, which is why dogs and cats mark their "turf" by urinating. Both chemical senses, particularly smell, are important mediums of communication in the animal kingdom.

Mechanisms of Taste and Smell

Scientists in the nineteenth century believed that human tongues have receptors for four basic tastes: sweet, sour, salty, and bitter. More current research, however, shows that the taste receptors on the tongue are more complicated than was previously thought. Still, it does seem to be the case that specific kinds of taste buds are clustered in certain areas. Taste buds, so named because they look like plant buds when viewed under a microscope, cover the tongue and, to a lesser extent, can be found on the cheek, throat, and roof of the mouth. As we shall see, however, some people have a greater concentration of taste buds than do others. In the mouth, saliva breaks down the chemical components of substances, which travel through the pores in the papillae (small protuberances on the surface of the tongue) to reach the taste buds themselves.

When specific proteins in food bind to receptors on the taste buds, these receptors send messages to the cerebral cortex, a surface layer on the brain that coordinates sensory information. And though taste buds in certain regions of the tongue have an affinity for particular flavors, as we discuss later, the intricacies of the neural and

chemical networks tend to suggest that nothing is clear-cut about this highly complex biological process.

OLFACTION: A DIRECT SENSE. Before modern times, several of the leading theories of vision maintained that the eye actually interacts with the objects it sees. Now we know that our eyes simply receive light reflected off those objects. By contrast, smelling is a direct experience, because we inhale microscopic portions of substances that have evaporated and make their way into the nasal cavity, where they chemically interact with sense receptors. Cells in the nose detect odors through receptor proteins on the cell surface, which bind to odor-carrying molecules. A specific odorant docks with an olfactory receptor protein in much the same way that a key fits into a lock. This, in turn, excites the nerve cell, causing it to send a signal to the brain.

Although there are many tens of thousands of odor-carrying molecule types in the world, meaning that there are as many different smells, there are only hundreds (or at most about 1,000) different types of olfactory receptors in even the most sensitive animal species. This finding has led scientists to speculate that not every receptor recognizes a unique odorant molecule; rather, similar odorants can bind to the same receptor. Another way to put this, in light of the lock and key analogy, is that a few loose-fitting odorant "keys" of roughly similar structure can enter the same receptor "lock."

Just as we sense smells directly, the olfactory sense is also direct in the way that signals are transmitted to the brain. Vision, by contrast, puts into play several steps: a receptor cell detects light and passes the signal to a nerve cell, which passes it on to another nerve cell in the central nervous system, which then relays it to the visual center of the brain. In olfaction, on the other hand, the olfactory nerve cells perform all these functions.

In most animals these cells take scent messages directly to the nerve cells of the olfactory bulb in the brain. With insects and other invertebrates whose brains are relatively simple, functioning primarily as clearinghouses for sensations, the olfactory nerves send signals to the olfactory ganglia, a mass of nerve tissue that connects nerve cells external to the brain and spinal cord. In higher animals, such as humans, olfactory signals go to the olfactory cortex, a structure in the brain where higher functions, such as memory and emotion, are coordinated with the sense of smell. Hence, as many people have observed, the sense of smell is linked strongly with long-term memory in a way that such senses as sight and touch are not.

REAL-LIFE APPLICATIONS

Taste Buds

Humans have only about 10,000 taste buds, whereas rabbits have 17,000 and cows some 25,000. This seems more than a little ironic, since humans enjoy by far the most varied diet. Both of the other animals are herbivores, meaning that they do not eat meat, nor are they accustomed to sweets and the many other varieties of taste in the diet of the average well-fed American. If anything, cows, with about 50% more taste buds than rabbits, eat a diet even more plain than that of their furry, fleet-footed fellow mammals.

Though our tasting equipment (that is, the chemoreceptors for taste in our tongues) may be much less sophisticated than that of cows or rabbits, the number of tastes our palate can recognize is as varied as a spectrum of color swatches at a paint store. Despite such variation, there are only a few basic tastes, most notably, the ones that once were thought to constitute primary tastes analogous to the primary colors: sweet, sour, salty, and bitter.

THE FOUR "BASIC TASTES." When you lick an ice cream cone, you may notice that you are experiencing the sweetness of it primarily at the tip of your tongue. This is not simply because you are licking it with the tip but also because there is a heavier concentration of sweetness receptivity in that area. On the other hand, if you eat a sour gumball, you experience the taste most notably on the sides of your tongue, where receptivity to sour tastes is strongest. Reception of salty tastes takes place near the front of the tongue, just behind the tip. As for bitter tastes, the focal point of receptivity appears to be near the back of the tongue. The latter may be a highly useful adaptive mechanism we have developed along the way, since many poisons are bitter, and the gagging reflex takes place near the back of the mouth. Not all bitter tastes are revolting, however: olives, which many people love, are

bitter as well, as is coffee when it has no cream or sugar to alter its flavor.

As we noted earlier, the organization of taste receptors on the tongue is not quite as simple as once was believed. For example, though our receptivity to sweetness seems to take place primarily at the tip, to a lesser extent we taste sweetness and other flavors all over the tongue. Furthermore, such flavors as sweet, sour, bitter, and salty are not the sum total of "taste" as we experience it; not only smell but also texture affects the taste of substances. Genetic and cultural factors also influence a person's unique tastes and may explain why one person loves sweets while another cannot get enough of tangy tastes.

Taste and Other Senses

Taste does not work alone; on the contrary, our sense of the smell, texture, and temperatures of foods affects our overall perception of its flavor and in some cases its desirability. When food is in the mouth, it produces a scent, which enters the nose through the nasopharynx, an opening that links the mouth and the nose. Because we experience smell more directly and our noses are more sensitive to olfactory sensations than our taste buds are to gustatory ones, people often experience the flavor of food first by its smell. This greatly affects our perception of what we eat.

For example, while many people like blue cheese, many others despise it, and this probably has more to do with its smell than with its taste. While its taste is rather tangy, it is not quite as "radical" as the aroma of this cheese, which has been compared to everything from old socks to vomit. Other cheeses, such as gorgonzola and, particularly, Limburger, are even more pungent and therefore have more than their share of detractors—but again, the smell is more extreme than the taste.

On a more pleasant note, anyone who has ever enjoyed a good steak or a hamburger cooked on an open grill will attest to the fact that a great deal of that enjoyment comes from the aromas of cooking. Usually it is the smell of a delectable food item, which we detect long before we taste it, that causes our salivary glands to begin operating, preparing us for the process of consuming and digesting the dish. Additionally, different types of cooking have particular smells and tastes associated with them, which people may find more or less appealing. For example, scrambled eggs cooked over an open campfire are likely (all other things being equal) to be more appealing to most people than eggs cooked in a skillet on an electric stove. But if the campfire is fueled with burning dung instead of wood, most Americans would choose the stove. In sparsely forested parts of the third world, however, animal dung is a principal form of fuel, and without it people might have to eat meals raw.

TEXTURE AND TEMPERATURE. Texture and temperature may have less impact on taste than does smell, but these are still significant factors. Take the example of three plates of French fries. One is limp and soggy in consistency, and another is so crispy that the French fry crunches like potato chips. The third, however, is just a bit crispy on the outside and just a bit soft on the inside. Most people, though certainly not all, would judge the third plate of French fry the most delectable—purely on the basis of texture.

By the same token, many people are less than enthusiastic about boiled okra, owing to its slimy consistency, whereas fried okra is more appealing to most Americans, since it lacks that gooey texture. Likewise, temperature plays more of a role than one might think. Many people, for example, find cold coffee unappealing, though others have a fondness for iced coffee, at least if it has milk and sweetener. Similarly, many Americans enjoy the combination of cold ice cream and hot pie or cobbler, partly because the contrast of temperatures adds to the overall flavor.

Different People, Different Sensations

Not all people "taste" the same—that is, not all people have the same sense of taste or the same level of acuity for distinguishing different flavors. One person may have 10–1,100 taste buds per square inch (6.45 cm^2) on the tongue, indicating a huge range of sensitivities with regard to gustatory data. Research also has shown that women, on average, have more taste buds than men, proving what many a woman has long asserted—that women have "better taste" than men.

Though it does appear that the average female has a more acute sense of gustation than the typical male, taste buds are not the only biological factor involved in recognizing flavors. For example, the amount of saliva a person naturally generates and the amount of salt that appears in one's saliva play a major role in determining an

individual's response to salty foods. A person whose mouth generates less saliva is more sensitive to the salt in foods, whereas a person prone to generating a greater quantity of saliva is less likely to taste the salt that has been added to a dish. That person is therefore more likely to add salt.

Ability to smell also varies from person to person, though it appears that a less acute sense of smell may be a sign not merely of fewer olfactory receptors but also of an actual olfactory disorders. Just as some people may be color-blind, it appears that others are "smell-blind." And just as being color-blind can have very serious consequences, for instance by causing a color-blind driver to miss a red light, much the same is true with an olfactory disorder. To a greater extent than one might immediately guess, smell serves a protective function. For example, without a sense of smell, one cannot tell if food is spoiled, unless, of course, it has reached such a state of putrefaction that it shows visible signs. For a person with an ordinary sense of smell, however, rotten food sends a signal through the olfactory receptors, which may cause a gag reflex when smelling food that has spoiled.

AGE AND SENSE OF TASTE. It is an experience familiar to many people, and it goes something like this. Let us say that in his boyhood, a man enjoyed a particular brand of candy, of which he could never get enough. Left to his own devices, he probably would have eaten so much that he would have become sick. The fact that this never happened had more to do with his parents—and the fact that his allowance money had to go for other things as well—than it did with his own natural sense of restraint. So he dreamed of the day when he became a grown-up, when he could eat whatever he wanted.

Eventually, he forgets this dream amid the many distractions of adolescence, but then one day many years later, as a grown man, he happens to see this particular item of candy in a store, and all his childhood memories come back to him. He buys several pieces, thrilled that he can enjoy in complete freedom what was once a rare treat. He can barely wait to get into his car, open the first piece, put it in his mouth—and then he recoils in disgust, thinking, *How did I ever enjoy that?* Disappointed, he throws away the rest of the candy.

The candy, of course, has not changed, but the man—and his taste buds—have. As we mature, so do our taste buds, and their numbers increase, leading to greater sophistication of taste. Children tend to like very basic tastes, particularly sweet and sour, and respond much less favorably to the subtlety in more complex dishes. This fact, combined with an increased awareness of health issues as one ages, explains why an adult might relish a broccoli casserole but find cotton candy so sweet as to be repugnant, whereas a child's reaction would probably be just the opposite.

Just as taste buds mature along with the people who own them, they also age. Every 3-10 days, on average, our taste buds regenerate themselves, replacing old ones that have been worn out by foods that are too hot, too cold, or otherwise too taxing to the chemoreceptors in our tongues. But as people grow older, their taste buds replace themselves less frequently, and therefore their sense of taste becomes less finely tuned. An older person may require much more sweetness or spice to taste a particular food.

CHEMORECEPTION IMPAIRMENT AND DISORDERS

Sense of smell also deteriorates with age; as we noted earlier, this can pose dangers, because a person depends on the sense of smell for protection more than one might imagine. For example, in addition to the inability to detect spoiled food, an elderly person would be far less likely to smell smoke if a building were on fire. Older people also are less likely to be cognizant of olfactory data that send messages concerning unpleasant smells of a less critical nature—body odor, for example.

Many of the problems of gustation and olfaction suffered by the elderly are reflected, at a much younger age, in the bodies of smokers. In addition to its many other negative effects, smoking deadens taste buds and desensitizes the olfactory receptors. It is not uncommon to see a heavy smoker salting pizza or some other food that for people with ordinarily functioning taste buds would not seem to require any salt. As for olfactory sensation, a smoker becomes accustomed to the reek of stale smoke and ashes.

On a more temporary basis, many people find their senses of taste and smell impaired by illness. A person with a cold or flu, even at its final stages, usually has enough congestion that the senses of both smell and taste are limited, if not almost nonexistent. In this instance, the lack



Taste and smell are not purely biological, but also reflect cultural factors. As late as the 1970s, most Americans would have said that the idea of eating raw fish was revolting. Today, America's cities bristle with Japanese restaurants that serve sushi, showing that cultural tastes can change. *(© Japack Company/Corbis. Reproduced by permission.)*

of ability to taste serves to illustrate the strong link between gustation and olfaction: the taste buds themselves are working fine, but the lack of smell, resulting from congestion, hinders the brain's ability to process flavor.

Taste and smell disorders. In addition to people whose olfactory and gustatory senses are impaired by age, illness, or smoking, between two million and four million Americans suffer from some sort of taste or smell disorder. The inability to taste or smell not only robs an individual of certain sensory pleasures, it also can be dangerous to one's mental health. Some psychiatrists believe that the lack of taste and smell can have a profoundly negative effect on a person's quality of life, leading to depression or other psychological problems.

Whereas impairments of smell and taste brought on by cold, flu, various viral and bacterial infections, and even allergies are usually temporary, some other illness-related taste and smell disorders are more long term. Such is the case with neurological disorders due to brain injury or diseases such as Parkinson's or Alzheimer's (conditions marked by tremors and mental deterioration, respectively). These conditions can cause more permanent damage to the intricate neural networks that process tastes and smells.

Drugs such as lithium, used to treat bipolar disorder (what used to be called manic depression) also may cause taste and smell disorders. This occurs because certain drugs (lithium is just one example among many) inhibit the action of certain enzymes, affect the body's metabolism, and interfere with the neural networks and receptors involved in tasting and smelling. Exposure to such environmental toxins as lead, mercury, insecticides, and solvents (e.g., paint thinner) also can damage taste buds and sensory cells in the nose or brain.

Culture and Chemoreception

One of the favorite delicacies in the Philippines is known as *dinuguan,* or pork cooked in pork blood. Chances are that a visitor from England or northern Europe, when told the constituents of the dish, would feel right at home; an American, however, most likely would try to think of an excuse to pass up this Filipino delight. To most Americans, it would seem that eating dinuguan, or the many varieties of blood pudding or blood sausage common in England and Scandinavia, is

simply "gross"—that it is objectively and unquestionably disgusting. But in the 1960s or even the 1970s, most Americans, even in large cities, would have said that the idea of eating raw fish was revolting. Today, however, America's cities and suburbs bristle with Japanese restaurants that serve sushi, an indication of the fact that cultural tastes can change.

As is discussed in Parasites and Parasitology, it should be noted that improperly cooked pork and fish (especially raw fish) are quite likely to serve as hosts for disease-carrying worms, so one should exercise care before sitting down to a plate of dinuguan or sushi. But then again, many Americans like their steaks on the rare side, and undercooked beef certainly has its share of pathogens (disease-carrying parasites) as well. It seems that it is not health concerns that explain our cultural double standards about certain food items.

Of course, Americans are not the only people with quirky standards regarding tastes and smells; in fact, every culture has its idiosyncrasies. In China it is not considered at all offensive for one's breath to smell heavily of onions; on the other hand, the smell of dairy products, virtually nonexistent in Chinese cuisine, is considered highly offensive. What does all of this prove? Only that taste and smell are not purely biological but also reflect cultural factors.

During the nineteenth century, many European scientists embraced a racist theory concerning the olfactory capabilities of different peoples around the world. According to this highly unscientific "theory," non-Europeans were more primitive than Europeans and therefore closer to animals, which meant that they had a stronger sense of smell. Completing the loop of this circular logic, subscribers to this nonsense maintained that because non-Europeans had a stronger sense of smell, it proved they were more primitive than Europeans!

Humans, Animals, and Smell

By the early twentieth century, physiologists had begun to explore much more scientific ideas concerning olfactory and gustatory abilities in humans—abilities that, needless to say, are not a function of race or ethnicity. Only one assumption of the old-fashioned European scientists was correct: that animals have a stronger sense of smell than do humans. The human nose is capable of detecting odors so faint that their proportion of the surrounding air is in the range of only a few parts per trillion. Many researchers are beginning to wonder whether smell does not play a greater role in human behavior and biology than previously was believed. For example, research has shown that only a few days after the birth of her baby, a human mother can smell the difference between a vest worn by her baby and one worn by another.

Nevertheless, the fact remains that the olfactory abilities of many animals are far beyond those of humans. This is a fact that hardly needs scientific verification, since most of us have observed dogs' reliance on their strong sense of smell. This explains why police use dogs to detect illegal drugs and explosives and to track runaway prisoners or the bodies of murder victims. Dogs are not the only animals gifted with acute senses of smell, which aid them in finding their way to specific targets. Salmon, for example, manage to find their way back to the streams where they were hatched, guided by their sense of smell. (For more about animals' navigational abilities, see Migration and Navigation.)

Most vertebrates other than humans have many more olfactory nerve cells in a proportionately larger olfactory epithelium, and this probably gives them much more sensitivity to odors. In addition, most land vertebrates have a specialized scent organ in the roof of their mouths called the vomeronasal organ, which gives them far more sensitivity to odors than humans have.

PHEROMONES. Some animals are known particularly for the odors they excrete, especially when it is an animal such as a skunk or stinkbug that puts off a repellent odor as a defense mechanism. But animals also send out much more subtle smells known as pheromones. Chemical substances produced and secreted by animals, pheromones serve as stimuli for behavioral responses on the part of other animals of the same species. Pheromones are common among insects as well as many vertebrates, but they are nonexistent among bird species.

Among so-called "social insects" such as bees and ants, pheromones play a particularly strong role. The queen honeybee gives off what is called the queen substance, a pheromone that acts to prevent the development of ovaries among workers, which are biologically unproductive females. Pheromones are vital for communication among

KEY TERMS

CHEMORECEPTION: A physiological process whereby organisms respond to chemical stimuli.

GUSTATORY: Of, or involving, the sense of taste (*gustation*).

INVERTEBRATE: An animal without an internal skeleton.

NERVOUS SYSTEM: A network, found in the bodies of all vertebrates, whose purpose is to receive and interpret stimuli and to transmit impulses. Parts of the nervous system include the brain, spinal cord, and nerves.

OLFACTORY: Of, or involving, the sense of smell (*olfaction*).

PHEROMONES: Chemical substances produced and secreted by animals, which serve as stimuli for one or more behavioral responses on the part of other animals of the same species.

RECEPTOR: A structure in the nervous system that receives specific stimuli and is affected in such a way that it sends particular messages to the brain. These messages are interpreted by the brain as sensations corresponding to the stimuli.

SENSE: The means by which an organism (usually an animal) receives signals regarding physical or chemical changes or both in its environment. Sometimes called *sensory reception* or *sensory perception.*

STIMULUS: Any phenomenon (i.e., an observable fact or event, such as an environmental change) that directly influences the activity or growth of a living organism.

VERTEBRATE: An animal with an internal skeleton.

social insects, which have little or no sense of sight. Ants, bees, and wasps send out smells to alarm others of danger, and ants may create a path of pheromones to guide others to a food source.

The function for which pheromones are most widely known, however, is as a sex attractant. Male musk deer are noted for their excretion of musk, which, as the result of to its pleasant and powerful smell, is often an ingredient in perfume manufacture. Though musk is a sex attractant, it is not a pheromone, which is a much less obvious scent and which, as we have noted, likely has an effect *only* on animals of the same species.

Experiments have shown that male mice who lack a gene for a pheromone receptor are likely to attempt to mate with males, simply because they cannot tell the difference. With humans, of course, it is easy to tell the difference between males and females on sight, but do humans also respond to pheromones? The fact that these chemicals theoretically could induce mating behavior led cologne and perfume makers long ago to embrace the idea of human pheromones, whose presence in a manufactured scent obviously would be a boon to many a single man or woman. Despite the enthusiastic claims of perfume manufacturers, however, many scientists have yet to be convinced that pheromones play a significant role for humans.

Regarding the fact that the human anatomy includes the vestige of a vomeronasal organ, the olfactory researcher Charles Wysocki told Lee Bowman in an article published on the National Library of Medicine Web site, "It's like the appendix—it's there, but it doesn't seem to do anything." As for scent makers' promises that pheromones will help users attract partners, Wysocki said, "Sure the claims are out there. ... 'All you have to do is put this on and you'll score.' But there's nothing in the published biomedical literature [to indicate] that we have any kind of pheromone that draws a partner." Research does suggest that people give off chemical messages that correspond to certain moods, but it is a long way from this to the idea of a spray-on aphrodisiac.

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BIOLOGICAL RHYTHMS

CONCEPT

People frequently talk about body clocks, a term that refers to the patterns of energy and exhaustion, functioning and resting, and wakefulness and sleep that characterize everyday life. In fact, the concept of the body clock, or circadian rhythm, is part of a larger picture of biological cycles, such as menstruation in mammalian females. Such cycles, which assume a variety of forms in a wide range of organisms, are known as biological rhythms. These rhythms may be defined as processes that occur periodically in an organism in conjunction with and often in response to periodic changes in environmental conditions—for example, a change in the amount of available light. Not all aspects of the body clock are part of day-to-day experience, and this is fortunate, since these interruptions in the healthy flow of biological rhythms can threaten the well-being of the human organism. Among these challenges to the ordered working of bodily "clocks" are jet lag, seasonal affective disorder (SAD), and other disorders linked to a range of causes, including drug use.

HOW IT WORKS

Understanding Biological Rhythms

Among the many varieties of biological rhythm, the most well known are those relating to sleep and wakefulness, which are part of the circadian rhythm that we discuss later in this essay. Circadian, or daily, cycles are only one type of biological rhythm. Some rhythms take place on a cycle shorter than the length of a day, while others are based on a monthly or even an annual pattern.

Nor do all cycles involve sleep and wakefulness: menstruation, for instance, is a monthly cycle related to the sloughing off of the lining of the uterus, a reproductive organ found in most female mammals. Another biological rhythm is the beating of the heart, which, of course, takes place at very short intervals. Nonetheless, the circadian rhythm is the most universal of biological cycles, and it is the focus of our attention in this essay.

BIOLOGICAL CLOCKS. In discussing the operation of biological rhythms, the term biological clock often is used. A biological clock is any sort of mechanism internal to an organism that governs its biological rhythms. One such mechanism, which we examine in the next section, is the pineal gland. Internal clocks operate independently of the environment but also are affected by changes in environmental conditions.

Examples of such alterations of conditions include a decrease (or increase) in the hours of available light due to a change of seasons or a change in time alteration due to rapid travel from west to east or north to south. In the latter instance, a condition known as jet lag—increasingly familiar to humans since the advent of regular air travel in the mid–twentieth century—may ensue.

The Pineal Gland

Governing human biological cycles—the "computer" that operates our biological clocks—is the pineal gland, a cone-shaped structure about the size of a pea located deep inside the brain. At one time, the great French philosopher and mathematician René Descartes (1596–1650) held that the pineal gland was actually the seat of the soul. Though it might seem absurd now that a respect-

ed thinker would seriously attempt to locate the soul in space, as though it were a physical object, Descartes's claim resulted from hours of painstaking dissection conducted on animals.

In searching for the human soul, Descartes sought that ineffable quality described some fifteen centuries earlier by the Roman emperor and philosopher Marcus Aurelius (121–180), who wrote, "This being of mine, whatever it really is, consists of a little flesh, a little breath, and the part which governs." As it turns out, the pineal gland *is,* in a sense, "the part which governs": it may not be the home of the soul (which, in any case, is not a question for science), but it does govern human circadian rhythms and thus has a powerful effect on the manner in which we experience the world.

MELATONIN. The pineal gland secretes two hormones (molecules that send signals to the body), melatonin and serotonin. During the late 1990s, melatonin became a popular over-the-counter treatment for persons afflicted with sleep disorders, because it is believed that the hormone is associated with healthful sleep. Scientists do not fully understand the role that melatonin plays in the body, although it appears that it regulates a number of diurnal, or daily, events.

In addition, melatonin seems to serve the function of controlling fat production, which is one reason why good sleep is associated not only with a healthy lifestyle but also with a healthy physique. Many health specialists maintain that for adults there is a close link between a "spare tire" (that is, fat accumulation around the waist) and stress, lack of sleep, and low melatonin levels.

Among the many roles melatonin plays in the body is its job of regulating glucose levels in the blood, which, in turn, serve to govern the production of growth hormone, or somatotropin. Growth hormone is associated with the development of lean body mass, as opposed to fat, which is why athletes involved in the Olympics and other major sporting competitions sometimes have illegally "doped" with it as a means of increasing strength. It is not surprising, then, to learn that children—who clearly need and use more growth hormone and who also need more hours of sleep than adults—also have higher melatonin levels.

SEROTONIN. Melatonin is not the only important hormone that is both secreted by the pineal gland and critical to the regulation of the body clock. Complementary to melatonin is serotonin, which is as important to waking functions as melatonin is to sleepiness. Like melatonin, serotonin serves several functions, including the regulation of attention.

Serotonin is among the substances responsible for the ability of a human with a healthily functioning brain to filter out background noise and sensory data. Thanks in part to serotonin, you are able to read this book without having your attention diverted by other sensory data around you: the voice of someone talking nearby, the sunlight or a bird singing outside, the hum of a light or a fan in the room.

By contrast, a person under the influence of the drug LSD (lysergic acid diethylamide) is not able to make those automatic filtering adjustments facilitated by serotonin. Instead, he or she is at the mercy of seemingly random intrusions of outside stimuli, such as the color of paint on a wall or the sound of music playing in the background. The secret of LSD's powerful hallucinatory effect can be attributed in part to the fact that it apparently mimics the chemistry of serotonin in the brain, "tricking" the brain into accepting the LSD itself as serotonin.

With regard to body clocks and biological rhythms, serotonin plays an even more vital governing role than does melatonin, since melatonin, in fact, is created by the chemical conversion of serotonin. On regular daily cycles the body converts serotonin to melatonin, thus influencing the organism to undergo a period of sleep. Then, as the sleeping period approaches its end, the body converts melatonin back into serotonin.

REAL-LIFE APPLICATIONS

Circadian Rhythms

The term *circadian* derives from the Latin *circa* ("about") and *dies* ("day"), and, indeed, it takes "about" a day for the body to undergo its entire cycle of serotonin-melatonin conversions. In fact, the cycle takes almost exactly 25 hours. Why 25 hours and not 24? This is a fascinating and perplexing question.

It would be reasonable to assume that natural selection favors those organisms whose body clocks correspond to the regular cycles of Earth's rotation on its axis, which governs the length of a

day—or, more specifically, a solar day. Yet the length of the human daily cycle has been confirmed in countless experiments, for instance, with subjects in an environment such as a cave, where levels of illumination are kept constant for weeks on end. In each such case, the subject's body clock adopts a 25-hour cycle.

POSSIBLE EXPLANATIONS FOR THE 25-HOUR CYCLE. One might suggest that the length of the cycle has something to do with the fact that Earth's rate of rotation has changed, as indeed it has. But the speed of the planet's rotation has *slowed,* because—like everything else in the universe—it is gradually losing energy. (This is a result of the second law of thermodynamics.)

About 650 million years ago, long before humans or even dinosaurs appeared on the scene, Earth revolved on its axis about 400 times in the interval required to revolve around the Sun. This means that there were 400 days in a year. By the time *Homo sapiens* emerged as a species about two million years ago, days were considerably longer, though still shorter than they are now. This only means that the 25-hour human body clock would have been even less compatible with the length of a day in the distant past of our species.

One possible explanation of the 25-hour body clock is the length of the lunar day, or the amount of time it takes for the Moon to reappear in a given spot over the sky of Earth. In contrast to the 24-hour solar day, the lunar day lasts for 24 hours and 50 minutes—very close in length to the natural human cycle. Still, the exact relationships between the Moon's cycles and those of the human body have not been established fully: the idea that lunar cycles have an effect on menstruation, for instance, appears to be more rumor than fact.

PEAKS AND TROUGHS. On the other hand, circadian rhythms do mirror the patterns of the Moon's gravitational pull on Earth, which results in a high and low tide each day. Likewise, the human circadian rhythm has its highs and lows, or peaks and troughs. In the circadian trough, which occurs about 4:00 A.M., body temperature is at its lowest, whereas at the peak, around 4:00 P.M., it reaches a high. A person may experience a lag in energy after lunchtime, but usually by about 4:00 in the afternoon, energy picks up—a result of the fact that the body has entered a peak time in its cycle.

This fact, by the way, points up the great wisdom of a practice common in Spanish-speaking countries and some other parts of the world: siestas. The siesta devotes one of the least productive parts of the day, the post-lunch lag, to rest, so that a person is equipped with energy for the rest of the afternoon and early evening—at precisely the time when energy is at a high. To compensate for the time "lost" on napping, many such societies maintain a later schedule, with offices closing in the early evening rather than late afternoon and with evening meals served at about 9:00 P.M.

Note that even though our body clocks run on a 25-hour day, they readily adjust to the 24-hour world in which we live. As long as a person is exposed to regular cycles of day and night, the pineal gland automatically adapts to the length of a 24-hour solar day. If a person has been living in a sunless cave, with no exposure to daylight for a length of time, it would take about three weeks for the pineal gland to reset itself, but thereafter it would track with Earth time consistently.

The adjustment of the body clock is not simply a matter of sending signals for sleep and wakefulness. In fact, the pineal gland is at the center of a complex information network that controls sleep cycles, body temperature, and stress-fighting hormones. Hence the link that we noted earlier between body temperature and circadian rhythms: just as the body reaches its lowest temperature in the circadian trough, it also enters a period of extremely deep sleep.

REGULATING THE BODY CLOCK. Tied in with these sleep patterns are many other bodily functions. For example, bodybuilders and others who work out with weights experience their greatest benefits not when lifting (which, in fact, tears muscles down rather than building them up) but when resting—and particularly when sleeping—after having worked out earlier in the day. Likewise, deep sleep is associated with growth, as we have noted. Furthermore, it appears that dreaming may be essential to the well-being of the psyche, providing an opportunity for the brain to "clean out" the signals and data it has been receiving for the preceding 16 hours of wakefulness.

Given these and other important functions associated with deep sleep, it follows that the maintenance of the body clock is of great importance to the health of the human organism. For-



View of the midnight sun in Lyngenfjord, Norway. The "body clock" can be disrupted by changes in the amount of available light, such as occur in regions of the extreme north that undergo periods of almost constant daylight from mid-May to late July. *(© Bettmann/Corbis. Reproduced by permission.)*

tunately, animals' brains are programmed to make adjustments of the body clock so as to accommodate the daily cycles of light and dark. We have discussed the means by which the human brain achieves this accommodation, but it is not the only animal brain thus equipped. "Bird brains" (quite literally) are similarly able to make an adjustment: whereas humans have a natural 25-hour clock, birds run on a 23-hour circadian cycle, but their pineal glands likewise assist them in adapting to the 24-hour solar day.

The brains of birds, humans, and other animals respond to environmental features known collectively as *zeitgebers* (German for "time givers"), which aid in the adjustment to the solar schedule. The most obvious example is the change from day to night, but there are other zeitgebers of which we are less aware in our ordinary experience. For example, Earth's magnetic field goes through its own 24-hour cycle, which subtly influences our biological rhythms.

Interfering with the Body Clock

In modern life humans often interfere with their own body clocks, either deliberately and directly or indirectly and by accident. On the one hand, a person may drink coffee to stay awake at night, but he or she also may experience a sleep disorder as a result of some other situation, which may or may not be the result of purposeful action. Examples of sleep disorders that are the by-product of other activities include jet lag as well as the malfunctioning of the body clock that often stems from recreational drug use.

The causes for interference with a person's body clock may be outside that person's control to one degree or another. Working at night, for instance, is a condition that almost never suits a human being, no matter how much a person may insist that he or she is a "night person." Nevertheless, a person may be required by circumstances, such as schedule, economic necessity, or job availability, to take a night job. Another example of interference with the body clock would be narcolepsy (a condition characterized by brief attacks of deep sleep) or some other condition that is either congenital (something with which a person is born) or symptomatic (a symptom of some other condition rather than a condition in and of itself).

WHITE NIGHTS. At least one example of human experience involving interference with the body clock relates to conditions *completely*

outside people's control. This is the situation of the "white nights" or "midnight sun," whereby regions in the extreme north—Russia, Alaska, and Scandinavia—undergo periods of almost constant daylight from mid-May to late July. (These are matched by a much less pleasant phenomenon: near constant darkness from mid-November to late January.)

During those times people often line their windows with dark material to make it easier to go to sleep in a world where the Sun is nearly as bright at 3:00 A.M. as it is at 3:00 P.M. The situation is even more pronounced in Antarctica, where researchers and adventurers may find themselves much closer to the South Pole than people in Saint Petersburg, Anchorage, or Oslo are to the North Pole.

In Antarctica the human population is much higher in the summer, a period that coincides with the depth of winter in the Northern Hemisphere, and scientists or mountaineers trekking through remote regions may be forced to sleep in tents that keep out the cold but let in the light. Usually, however, the rugged conditions of life near the South Pole involve such exertions that by nighttime people are ready to sleep, light or no light.

SOME SLEEP DISORDERS. Few people ever get to experience the white nights, but almost everyone has suffered through a temporary bout of insomnia—a condition known specifically as *transient insomnia.* An unfortunate few suffer from chronic insomnia or some other sleep disorder. Insomnia, the inability to go to sleep or to stay asleep, is one of the two most common sleep disorders, the other being hypersomnia, or excessive daytime sleepiness.

Transient forms of insomnia are usually treatable with short-term prescription drugs, but more serious conditions qualify as actual disorders and may require long-term treatment. These disorders may have as their cause drug use (either prescription or illegal) as well as medical or psychological problems. Among the most common of these more specialized disorders is apnea, the regular cessation of breathing whose most noticeable symptom is snoring.

Apnea, which affects a large portion of the United States population, is a potentially very serious condition that can bring about suffocation or even death. More often its effects are less dramatic, however, and manifest in hypersomnia, which is a result of lost sleep due to the fact that the sufferer actually is waking up numerous times throughout the night.

At the other extreme from apnea, in terms of prevalence among the population, is Kleine-Levin syndrome, which typically affects males in their late teens or twenties. The syndrome may bring about dramatic symptoms that range from excessive sleepiness, overeating, and irritability to abnormal behavior, hallucinations, and even loss of sexual inhibitions. Added to this strange mix is the fact that Kleine-Levin syndrome typically disappears after the person reaches the age of 40.

JET LAG. There are numerous classes of sleep disorders, among them circadian rhythm disorders—those related to jet lag or work schedules. As we have seen, the pineal gland can adjust easily from a natural 25-hour cycle to a 24-hour one, but it can do so only gradually, and it cannot readily adapt to sudden changes of schedule, such as those brought about by air travel.

Jet lag is a physiological and psychological condition in humans that typically includes fatigue and irritability; it usually follows a long flight through several time zones and probably results from disruption of circadian rhythms. The name is fitting, since jet lag is associated almost exclusively with jets: traveling great distances by ship, even at the speeds of modern craft, allows the body at least some time to adjust.

Older modes of travel were too slow to involve jet lag; for this reason, the phenomenon is a relatively recent one. The only people who manage to experience jet lag without riding in a jet are those traveling in even faster craft—that is, astronauts. An astronaut orbiting Earth in a space shuttle experiences rapid shifts from day to night; if manned vessels ever go out into deep space, scientists will face a new problem: assisting the adjustment of circadian cycles to that sunless realm.

On a much more ordinary level, there is the jet lag of people who travel from the United States East Coast to Europe or between the East Coast and West Coast of the United States. The worst kinds of jet lag occur when a person flies from west to east across six or more time zones: anyone who flies to Europe from the East Coast is likely to spend much of the first day after arrival sleeping rather than sightseeing. Thereafter, it may take up to ten days (usually as long

as or longer than most European vacations) for the body to adjust fully.

By contrast, someone who has flown from the East Coast to the West Coast feels unexpected energy. The reason is that when it is 6:00 A.M. in the Pacific time zone, it is 9:00 A.M. in the eastern time zone, to which a person's body clock (in this particular scenario) is still adapted. Therefore, at 6:00 in the morning, the newly arrived traveler will feel as good as he or she would normally feel at 9:00 A.M. back east. Conversely, at 9:00 P.M. in the west, it is midnight in the east. This means that the traveler is likely to feel tired long before his or her ordinary bedtime.

There are steps one can take to avoid, or at least minimize the effects of, jet lag. One is to ensure a regular sleep schedule prior to traveling, so as to minimize the effects of sleep deprivation, if the latter does occur. It is even better if one can, in the days prior to leaving, adopt a schedule adjusted to the new time zone. For example, if one were traveling from the East Coast to California, one would start going to bed three hours earlier, and rising three hours earlier as well. Changing eating habits in the days prior to departure may also help. Some experts on the subject recommend a four-day period in which one alternates heavy eating (days one and three) and very light eating (days two and four.) It is believed that high-protein breakfasts stimulate the active, waking cycle, while high-carbohydrate evening meals stimulate the resting cycle; conversely, depriving the liver of carbohydrates may prepare the body clock to reset itself.

ON THE NIGHT SHIFT. At least the body does adjust to jet lag; on the other hand, it may never become accustomed to working a night shift. If you stay up all night studying for a test, you will find that around 4:00 A.M. you hit a "lull" when you feel sleepy—and because of the lowered temperature at the circadian trough, you also feel cold. You might assume that this situation would improve if you worked regularly at night, but the evidence suggests that it does not.

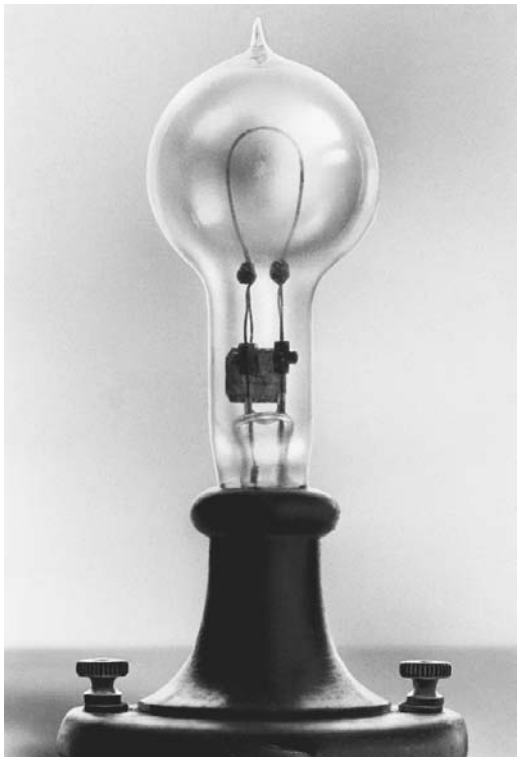
As long as a person lives in a sunlit world of 24-hour solar days, the body clock remains adapted to that schedule, and this will be true whether the person is at home and in bed or at work behind a desk or counter during the hours of night. In other words, the person always will hit the circadian trough about 4:00 A.M. This is one of the reasons why most people find the idea of working at night so unattractive, even though it is clear that in our modern society some night-shift positions are essential.

People who have offices in their homes may find it beneficial to work at late hours, when the phone is not ringing and the world is quiet, but the "extra time" gained by working at night ultimately is counterbalanced by the body's reaction to changes in its biological rhythms. Such is also the case with night-shift workers, who never really adjust to their schedules even after years on the job.

There *is* such a thing as a "night person," or someone with a chronic condition known as *delayed sleep phase syndrome.* A person with this syndrome is apt to feel most alert in the late evening and night, with a corresponding lag of energy in the late mornings and afternoons. Even so, given the role of sunlight in governing the body clock, the condition does not really lend itself to regular night work but rather merely causes a person to experience problems adapting to the schedule maintained by most of society. One possible means of dealing with this problem is to go to bed three hours later than would be normal for an ordinary 9-to-5 schedule, and wake up three hours later as well; unfortunately, that is not practical for most people. Another treatment applied with success is exposure of a person to artificial, high-intensity, full-spectrum light, which augments the effect of sunlight, between the hours of 7:00 and 9:00 A.M.

COLONIZING THE NIGHT? In this vein it is interesting to note that some of the optimistic predictions made in 1987 by Murray Melbin in his fascinating book *Night as Frontier: Colonizing the World After Dark* have not come to pass. Melbin, who explains circadian rhythms and the body clock in a highly readable and understandable fashion, makes a brilliant analysis of the means by which industrialized societies have extended their daily schedules into the nighttime hours. Thus, to use his analogy, such societies have "colonized" the night.

Until the invention in 1879 of the first successful incandescent lamp by the American inventor Thomas Edison (1847–1931), activity at night was limited. Torches, crude lamps, and candles in ancient times; metal lamps in the Middle Ages; and the various oil-burning lamps that applied the glass lantern chimney devised in 1490 by the Italian scientist and artist Leonardo



Until Thomas Edison invented the first successful incandescent lamp in 1879, activity at night was limited. With electric lighting, industrialized societies have been able to "colonize" the night, extending daytime activities into the nighttime hours. *(© Bettmann/Corbis. Reproduced by permission.)*

da Vinci (1452–1519) all made it possible for a person to read at night and to perform other limited functions. After their introduction in the nineteenth century, street lamps in London, the first of their kind, made the streets safe for walking at late hours, but travel, large gatherings, and outdoor work after dark remained difficult before the advent of electric light.

Since 1879 the Western world has indeed "colonized" the night with all-night eateries, roads that are never free of traffic, and round-the-clock entertainment on radio, TV, and now the Internet. There are even hardware stores open all night in some major cities. Certainly today there are more gas stations, restaurants, television programs, and customer-service telephone lines that operate 24 hours than there were in 1987, when Melbin wrote his book, but it is unlikely that Americans will ever fully "colonize" the night in the thoroughgoing fashion that their ancestors colonized the New World. An example of the limits to night colonization is in air travel.

Before the events of September 11, 2001, when terrorists crashed hijacked planes into the World Trade Center in New York City and the Pentagon in Washington, D.C., the burden on America's airports had become almost unbearable. The concourses of Hartsfield International in Atlanta, Georgia, the world's busiest airport, were a nonstop melee of people, luggage, and noise, as travelers fought to change flights or pick up their bags. One obvious solution to the problem would have been to adopt a round-the-clock airport schedule, with flights regularly leaving at 3:00 or 4:00 in the morning.

No airport rushed to enact such a measure, however, and after September 11 heightened security concerns made it unlikely that any facility would adopt a 24-hour schedule, with the additional security threats it entailed. For a time at least, the volume of air traffic decreased dramatically, but even as it climbed back up in the months after the terrorist attacks, airports continued to operate on their ordinary schedules. The reason appears to be the difficulty of persuading people to adjust to a late-night schedule—that is, finding enough people willing to fly in the middle of the night and enough baggage handlers and ticket agents willing to service them. There are, it seems, limits to the extent to which nighttime can be colonized.

Other Examples of Biological Rhythms

Although the circadian rhythms of sleep and wakefulness are particularly important examples of biological cycles, they are far from the only ones. Not all rhythms, in fact, are circadian. Some are ultradian, meaning that they occur more than once a day. Examples include the cycles of taking in fluid and forming urine as well as cell-division cycles and cycles related to hormones and the endocrine glands that release them. For instance, the pituitary gland in the brain of a normal male mammal secretes hormones about every one to two hours during the day.

The overall cycle of sleeping and waking is circadian, but there is an ultradian cycle within sleep as the brain moves from drowsiness to REM (rapid eye movement, or dream, sleep) to dozing, then to light and deep sleep, and finally to slow-wave sleep. Over the course of the night, this cycle, which lasts about 90 minutes, repeats itself several times. Among the functions affected by



A Rocky Mountain goat sheds its thick winter fur. The shedding of fur, skin, or antlers is one example of a circannual cycle, which takes a year to complete. *(© W. Wayne Lockwood, M.D./Corbis. Reproduced by permission.)*

this cycle are heart rate and breathing, which slow down in deep sleep. Additionally, heartbeat and respiration are themselves ultradian cycles of very short duration.

Menstruation and other infradian cycles. In contrast to the ultra-quick ultradian cycles of the beating heart and the lungs' intake and outflow of oxygen, there are much longer infradian, or monthly, cycles. By far the most common is menstruation, which begins when a female mammal reaches a state of physical maturity and continues on a monthly basis until she is no longer able to conceive offspring.

When she becomes pregnant, the menstrual cycle shuts down and, in some cases, does not resume until several months after delivery of the offspring. Assuming she is in good health, the human female will experience fairly regular menstrual periods at intervals of 28 days. Among human females, it has long been known that the menstrual cycles of women who live or work in close proximity to one another tend to come into alignment. For example, college girls on the same floor in a dormitory are likely to share menstrual cycles.

The reasons for this alignment of menstrual cycles are not completely understood. Nor is the cause of the 28-day cycle evident. If it were the result of the Moon's cycles, all women on Earth would have menstrual cycles that last 29.5 days, which is how long it takes the Moon to travel around Earth. Furthermore, if there were a clear connection between the Moon and menstruation, the periods of all menstruating females on Earth would be aligned with the Moon's phases. Neither of these, of course, is the case.

Circannual cycles. Longer still than infradian cycles, circannual cycles, as their name suggests, take a year to complete. Among them is the cycle of dormancy and activity marked by the hibernation of certain species in the winter. There are also certain times of the year when animals shed things—fur, skin, antlers, or simply pounds. Likewise, at some points in the year animals gain weight.

People are affected strongly by the seasonal changes associated with the circannual cycle. There is almost no person who lives in a temperate zone (that is, one with four seasons) who is not capable of calling strong emotions to mind when imagining the sensations associated with winter, spring, summer, or fall. Some sensations,

KEY TERMS

BIOLOGICAL CLOCK: A mechanism within an organism (for example, the pineal gland in the human brain) that governs biological rhythms.

BIOLOGICAL RHYTHMS: Processes that occur periodically in an organism in conjunction with and often in response to periodic changes in environmental conditions.

CHRONOBIOLOGY: A subdiscipline of biology devoted to the study of biological rhythms.

CIRCADIAN RHYTHM: A biological cycle that takes place over the course of approximately a day. In humans circadian rhythms run on a cycle of approximately 25 hours and govern states of sleep and wakefulness as well as core body temperature and other biological functions.

HORMONE: Molecules produced by living cells, which send signals to spots remote from their point of origin and which induce specific effects on the activities of other cells.

INFRADIAN RHYTHM: A biological cycle that takes place over the course of a month.

JET LAG: A physiological and psychological condition in humans that typically includes fatigue and irritability; it usually follows from a long flight through several time zones and probably results from disruption of circadian rhythms.

MENOPAUSE: The point at which menstrual cycles cease, a time that typically corresponds to the cessation of the female's reproductive abilities.

MENSTRUATION: Sloughing off of the lining of the uterus, which occurs monthly in nonpregnant females who have not reached menopause (the point at which menstrual cycles cease) and which manifests as a discharge of blood.

PINEAL GLAND: A small, usually cone-shaped portion of the brain, often located between the two lobes, that plays a principal role in governing the release of certain hormones, including those associated with human circadian rhythms.

ULTRADIAN RHYTHM: A biological cycle that takes place over the course of less than a day. Compare with *circadian rhythm.*

however, are better than others, and though there can be negative associations with spring or summer, by far the season most likely to induce ill effects in humans is winter.

The thirteen weeks between the winter solstice in late December and the vernal equinox in late March have such a powerful impact on the human psyche that scientists have identified a mental condition associated with it. It is SAD, or seasonal affective disorder, which seems to be related to the shortened days (and thus, ultimately, to the altered circadian rhythm) in wintertime.

As we have noted, the body responds to the onset of night and sleep by the release of melatonin, but when darkness lasts longer than normal, melatonin secretions become much more pronounced than they would be under ordinary conditions. The result of this hormone imbalance can be depression, which may be compounded by other conditions associated with winter. Among these conditions is "cabin fever," or restlessness brought about by lengthy confine-

ment indoors. An effective treatment for SAD is exposure to intense bright light.

Studying Biological Rhythms

Treatment of SAD is just one example of the issues confronted by scientists working in the realm of chronobiology, a subdiscipline devoted to the study of biological rhythms. Naturally, a particularly significant area of chronobiological study is devoted to sleep research. The latter is a relatively new field of medicine stimulated by the discovery of REM sleep in 1953. In addition to studying such disorders as sleep apnea, sleep researchers are concerned with such issues as the effects of sleep deprivation and the impact on circadian rhythms brought about by isolation from sunlight.

Note that the scientific study of biological rhythms has nothing to do with "biorhythms," a fad that peaked in the 1970s but still has its adherents today. Biorhythms are akin to astrology in their emphasis on the moment of a person's birth, and though biorhythms have a bit more scientific basis than astrology, that in itself is not saying much. As we have seen, biological rhythms do govern much of human life, but the study of these rhythms does not offer special insight into the fate or future of a person—one of the principal claims made by adherents of biorhythms. As with all pseudosciences, belief in biorhythms is maintained by emphasizing those examples that seem to correlate with the theory and ignoring or explaining away the many facts that contradict it.

An example of scientific research in chronobiology and related fields is the work of the psychologist Stephany Biello at Glasgow University in Scotland, who in June 2000 announced findings linking the drug, ecstasy, to long-term damage to the body clock. As with LSD and many another drug, ecstasy plays havoc with serotonin and may exert such a negative impact on the pathways of serotonin release in the pineal gland that it permanently alters the brain's ability to manufacture that vital hormone. Thus the drug, which induces a sense of euphoria in users, can induce serious sleep and mood disorders as well as severe depression.

WHERE TO LEARN MORE

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LEARNING AND BEHAVIOR

BEHAVIOR

INSTINCT AND LEARNING

MIGRATION AND NAVIGATION

BEHAVIOR

CONCEPT

In biology the term behavior refers to the means by which living things respond to their environments. At first glance, this might seem to encompass only animal behavior, but, in fact, plants display observable behavior patterns as well. One of the principal manifestations of plant behavior is tropism, a response to a stimulus that acts in a particular direction, thus encouraging growth either toward or away from that stimulus. Behavior in plants is primarily a matter of response to stimuli, which may be any one of a variety of influences that derive either from inside or outside the organism. Response to stimuli is automatic, and even humans are capable of making these types of programmed responses. In most cases, behaviors in organisms are designed to ensure their survival. Such is the case, for instance, with the complex of behaviors known as territoriality, whereby animals defend what they perceive to be their own.

HOW IT WORKS

Stimulus and Response

A stimulus is any phenomenon that directly influences the activity or growth of a living organism. *Phenomenon,* meaning any observable fact or event, is a broad term and appropriately so, since stimuli can be of so many varieties. Chemicals, heat, light, pressure, and gravity all can serve as stimuli, as indeed can any environmental change. Nor are environmental changes limited to the organism's external environment. In some cases its internal environment can act as a stimulus, as when an animal reaches the age of courtship and mating and responds automatically to changes in its body.

All creatures, even humans, are capable of automatic responses to stimuli. When a person inhales dust, pepper, or something to which he or she is allergic, a sneeze follows. The person may suppress the sneeze (which is not a good practice, since it puts a strain on blood vessels in the head), but this does not stop the body from responding automatically to the irritating stimulus by initiating a sneeze. Similarly, plants respond automatically to light and other stimuli in a range of behaviors known collectively as *tropisms,* which we explore later in this essay.

INNATE AND LEARNED BEHAVIOR. Not all responses to stimuli are automatic, however. Certainly not all behavior on the part of higher animals is automatic, though, as we have noted, even humans are capable of *some* automatic responses. In general, behavior can be categorized as either innate (inborn) or learned, but the distinction is frequently unclear. In many cases it is safe to say that behavior present at birth is innate, but this does not mean that behavior that manifests later in life is learned. (Later in this essay we look at an example of this behavior as it relates to chickens and pecking.)

Behavior is considered innate when it is present and complete without any experience whereby it was learned. At the age of about four weeks, human babies, even blind ones, smile spontaneously at a pleasing stimulus. Like all innate behavior, babies' smiling is stereotyped, or always the same, and therefore quite predictable. Plants, protista (single-cell organisms), and animals that lack a well-developed nervous system rely on innate behavior. Higher animals, on the

other hand, use both innate and learned behavior. A fish is born knowing how to swim, whereas a human or a giraffe must learn how to walk.

Ethology

Ethology is the study of animal behavior, including its mechanisms and evolution. The science dates back to the British naturalist Charles Darwin (1809–1882), who applied it in his research concerning evolution by means of natural selection (see Evolution). Darwin presented many examples to illustrate the fact that, in addition to other characteristics of an organism, such as its morphologic features or shape, behavior is an adaptation to environmental demands and can increase the chances of species survival.

The true foundations of ethology, however, lie in the work of two men during the period between 1930 and 1950: the Austrian zoologist Konrad Lorenz (1903–1989) and the Dutch ethologist Nikolaas Tinbergen (1907–1988). Together with the Austrian zoologist Karl von Frisch (1886–1982), most noted for his study of bee communication and sensory perception, the two men shared the 1973 Nobel Prize in physiology or medicine.

Lorenz and Tinbergen, who together are credited as founders of scientific ethology, contributed individually to the discipline and, during the mid–twentieth century, worked together on a theory that animals develop formalized, rigid sequences of action in response to specific stimuli. According to Lorenz and Tinbergen, animals show fixed-action patterns (FAPs) of behavior which are strong responses to particular stimuli. Later in this essay, we look at examples of FAPs in action. In addition, Lorenz put forward the highly influential theory of imprinting, discussed briefly in this essay and in more detail elsewhere (see Instinct and Learning).

Behaviorism and Conditioning

The development of ethology by Lorenz and Tinbergen occurred against the backdrop of the rise of the behaviorist school in the realms of philosophy, psychology, and the biological sciences. This school of thought had its roots in the late nineteenth century, with the writings of a number of philosophers and psychologists as well as practical scientists, such as the Russian physiologist Ivan Pavlov (1849–1936). Pavlov showed that an animal can be trained to respond to a particular stimulus even when that stimulus is removed, so long as the stimulus has been associated with a secondary one.

Pavlov began his now famous set of experiments by placing powdered meat in a dog's mouth and observing that saliva flowed into the mouth as a reflex reaction to the introduction of the meat. He then began ringing a bell before he gave the dog its food. After doing this several times, he discovered that the dog salivated merely at the sound of the bell. Many experiments of this type demonstrated that an innate behavior can be modified, and thus was born the scientific concept of conditioning, or learning by association with particular stimuli.

The variety of conditioning applied by Pavlov, known as *classical conditioning,* calls for pairing a stimulus that elicits a specific response with one that does not, until the second stimulus elicits a response like the first. Classical conditioning is contrasted with operant conditioning, which involves administering or withholding reinforcements (that is, rewards) based on the performance of a targeted response.

Operant conditioning. During operant conditioning, a random behavior is rewarded and subsequently retained by an animal. According to operant conditioning theory, if we want to train a dog to sit on command, all we have to do is wait until the dog sits and then say, "Sit," and give the dog a biscuit. After a few repetitions, the dog will sit on command because the reward apparently reinforces the behavior and fosters its repetition.

Human parents apply operant conditioning when they admonish their offspring with such phrases as "You can't watch TV until you've cleaned your room." Likewise, young chimpanzees learn through a form of operant conditioning. By observing their parents, young chimps learn how to strip a twig and then use it to pick up termites (a tasty treat to a chimpanzee) from rotten logs. Their behavior thus is rewarded, an example of the way that operant conditioning enables animals to add new, noninherited forms of behavior to their range of skills.

Though the theory of operant conditioning goes back to the work of the American psychologist Edward L. Thorndike (1874–1949), by far its most famous proponent was another American psychologist, B. F. Skinner (1904–1990). In applying operant conditioning to human beings,

Skinner and his followers took the theory to extremes, maintaining that humans have no ideas of their own, only conditioned responses to stimuli. Love, courage, faith, and all the other emotions and attitudes that people hold in high esteem are, according to this school of thought, simply a matter of learned responses, rather like a parrot making human-like sounds to earn treats. This extreme form of behaviorism is no longer held in high regard within the scientific or medical communities.

Real-Life Applications

Behavior in Plants

As noted earlier, the term *behavior* would seem at first glance to apply only to animals and not to plants. Certainly the majority of attention in behavioral studies, outside the realm of humans, is devoted to ethology, but plants are not without their observable behavioral characteristics. These features primarily manifest in the form of tropism, a response to a stimulus that acts in a particular direction, thus encouraging growth either toward or away from that stimulus. Tropism primarily affects members of the plant kingdom, though it has been observed in algae and fungi as well.

Though the word tropism itself may be unfamiliar to most people, the phenomenon itself is not. There are plenty of opportunities in daily life to observe the response of plants to energy, substances, or forms of stimulation. For example, perhaps you have noticed the way that trees or flowers grow toward sunlight, even bending in their growth if it is necessary to reach the energy source. Similarly, plants in a parched region are likely to develop roots directed laterally toward a water source.

Among the various forms of tropism are phototropism (response to light), geotropism (response to gravity), chemotropism (response to particular chemical substances), hydrotropism (response to water), thigmotropism (response to mechanical stimulation), traumatropism (response to wounds), and galvanotropism or electrotropism (response to electric current). Most of these types involve growth toward a stimulus, a phenomenon known as positive growth, or orthotropism. Plants tend to grow toward light or water, for instance. On the other hand, some kinds of stimuli tend to evoke diatropism, or growth away from the stimulus. Such is bound to be the case, for instance, with traumatropism and electrotropism.



One example of innate animal behavior is the reflex, a simple, inborn, automatic response to a stimulus by a part of an organism's body. Such a mechanism is at work, for instance, when jellyfish withdraw their tentacles. *(© Henry Horenstein/Corbis. Reproduced by permission.)*

Tropism, along with movement due to changes in water content, is one of the two principal forms of innate behavior on the part of plants. In general, stems and leaves experience positive phototropism, as they grow in the direction of a light source, the Sun. At the same time, roots exhibit positive gravitropism, or growth toward the gravitational force of Earth, as well as positive hydrotropism, since they grow toward water sources below ground. On the other hand, a plant may move in a specific way regardless of the direction of the stimulus. Such movements are temporary, reversible, and result from changes in the water pressure inside the plant.

Animal Behavior

An excellent example of an innate animal behavior, and one in which humans also take part, is



In contrast to simple fixed-action patterns of behavior, or FAPs, are complex programmed behavior patterns, which comprise several steps and are much more complicated. One type of complex behavior is the building of dams by beavers. *(© Harry Engels/Nas. Photo Researchers. Reproduced by permission.)*

the reflex. A reflex is a simple, inborn, automatic response to a stimulus by a part of an organism's body. The simplest model of reflex action involves a receptor and sensory neuron and an effector organ. Such a mechanism is at work, for instance, when certain varieties of coelenterate (a phylum that includes jellyfish) withdraw their tentacles.

More complex reflexes require processing interneurons between the sensory and motor neurons as well as specialized receptors. These neurons send signals across the body, or to various parts of the body, as, for example, when food in the mouth stimulates the salivary glands to produce saliva or when a hand is pulled away rapidly from a hot object.

Reflexes help animals respond quickly to a stimulus, thus protecting them from harm. By contrast, learned behavior results from experience and enables animals to adjust to new situations. If an animal exhibits a behavior at birth, it is a near certainty that it is innate and not learned. Sometimes later in life, however, a behavior may appear to be learned when, in fact, it is a form of innate behavior that has undergone improvement as the organism matures.

For example, chickens become more adept at pecking as they get older, but this does not mean that pecking is a learned behavior; on the contrary, it is innate. The improvement in pecking aim is not the result of learning and correction of errors but rather is due to a natural maturing of muscles and eyes and the coordination between them.

FAPs. In studying fixed-action patterns of behavior, or FAPs, Lorenz and Tinbergen observed numerous interesting phenomena. Male stickleback fish, for example, recognize potential competition—other breeding stickleback males—by the red stripe on their underside and thus engage in the FAP of attacking anything red on sight. Tinbergen discovered that jealous stickleback males were so attuned to the red stripe that they tried to attack passing British mail trucks, which were red, when they could see them through the glass of their tanks. Tinbergen termed the red stripe a behavioral releaser, or a simple stimulus that brings about a FAP.

Once a FAP is initiated, it continues to completion even if circumstances change. If an egg rolls out of a goose's nest, the goose stretches her neck until the underside of her bill touches the egg. Then she rolls the egg back to the nest. If someone takes the egg away while she is reaching for it, the goose goes through the motions anyway, even without an egg. Not all animal behavior is quite so predictable, however. In contrast to FAPs are complex programmed behavior patterns, which comprise several steps and are much more complicated. Birds making nests or beavers building dams are examples of complex programmed behavior.

IMPRINTING. As we noted earlier, Lorenz initiated the study of a learning pattern that came to be known as *imprinting.* Witnessed frequently in birds, imprinting is the learning of a behavior at a critical period early in life, such that the behavior becomes permanent. The very young bird or other organism is like wet concrete, into which any pattern can be etched; once the concrete has dried, the pattern is set.

Newly hatched geese are able to walk. This is something they learn the moment they are hatched, and they do so by following their parents. But how, Lorenz wondered, do young geese distinguish their parents from all other objects in their environments? He discovered that if he



ROCKY MOUNTAIN BIGHORN RAMS MEET HEAD TO HEAD AT THE BOUNDARIES OF THEIR RESPECTIVE TERRITORIES. USING THEIR HORNS, THESE RAMS WILL STRONGLY DEFEND THEIR TERRITORIES AGAINST INVADERS. *(© W. Perry Conway/Corbis. Reproduced by permission.)*

removed the parents from view the first day after the goslings hatched and if he walked in front of the young geese at that point, they would follow him. This tactic did not work if he waited until the third day after hatching, however.

Lorenz concluded that during a critical period following birth, the goslings follow their parents' movement and learn enough about their parents to recognize them. But since he also had determined that young geese follow any moving object, he reasoned that they first identify their parents by their movement, which acts as a releaser for parental imprinting. (Imprinting is discussed further in Instinct and Learning.)

INTERACTIVE BEHAVIOR

Much of an animal's behavior (this is true of the human animal as well) takes place in interaction with others. This interaction may include rudimentary forms of communication, such as bee dances, studied by Lorenz and Tinbergen's colleague Frisch. As he showed in perhaps the most important research of his career, bees communicate information about food supplies, including their direction and the distance to them, by means of two different varieties of "dance," or rhythmic movement. One is a circling dance, which informs the other bees that food is near (about 250 ft., or 75 m, from the hive), and the other is a wagging dance, which conveys the fact that food is farther away.

There are numerous other forms of communication using one or more sense organs. Birds hear each other sing, a dog sees and hears the spit and hiss of a cornered cat, and ants lay down scent signals, or pheromones, to mark a trail that leads to food. This is only one level of interactive behavior, however. Quite a different variety of interaction is courtship, discussed in Reproduction. Other forms of interactive behavior include the establishment of an animal's territory, a subject we discuss at the conclusion of this essay.

LIFE IN COMMUNITIES. Interactive behavior comes into play when animals live in close proximity to one another. Certainly there are benefits to group life for those species that practice it: the group helps protect individuals from predators and, through cooperation and division of labor, ensures that all are fed and sheltered. In order to be workable, however, a society must have a hierarchy. Thus, in a situation quite removed from the human ideals of freedom and democracy, insect and animal societies are ones in which every creature knows its place and sticks to it.

Bees, ants, and termites live in complex communities in which some individuals are responsible for finding food, others defend the colony, and still others watch over the offspring. In such a highly organized society, a dominance hierarchy or ranking system helps preserve peace and discipline. Chickens, for example, have a pecking order from the most dominant to the most submissive. Each individual knows its place in the order and does not challenge individuals of higher rank. This, again, is quite unlike humans, who at least occasionally step out of line and challenge bullies; by contrast, that never happens with chickens (fittingly enough).

Territoriality

Almost everyone has seen a dog "mark its territory" by urinating on a patch of ground or has watched a cat arch its back in fury at an intruder to what it perceives as its territory. In so doing, these household pets are participating in a form of behavior that cuts across the entire animal kingdom: territoriality, or the behavior by which an animal lays claim to and defends an area against others of its species and occasionally against members of other species as well.

The physical size of the territory defended is extremely varied. It might be only slightly larger than the animal itself or it might be the size of a small United States county. The population of the territory might consist of the animal itself, the animal and its mate, an entire family, or an entire herd or swarm. Time is another variable: some animals maintain a particular territory year-round, using it as an ongoing source of food and shelter. Others establish a territory only at certain times of the year, when they need to do so for the purposes of attracting a mate, breeding, or raising a family.

Territorial behavior offers several advantages to the territorial animal. An animal that has a "home ground" can react quickly to dangerous situations without having to seek hiding places or defensible ground. By placing potential competitors at spaced intervals, territoriality also prevents the depletion of an area's natural resources and may even slow down the spread of disease. Furthermore, territorial behavior exposes weaker animals (which are unable to defend their territory) to attacks by predators and thus assists the process of natural selection in building a stronger, healthier population.

Examples of territories. A territory established only for a single night, for the sole purpose of providing the animal or animals with a place to rest, is known as a roost. Even within the roost, there may be a battle for territory, since not all spots are created equal. Because roosting spots near the interior are the safest, they are the most highly prized.

Another type of specialized territory is the lek, used by various bird and mammal species during the breeding season. Leks are the "singles bars" of the animal world: here animals engage in behavior known as *lekking,* in which they display their breeding ability in the hope of attracting a mate. Not surprisingly, leks are among the most strongly defended of all territories, since holding a good lek increases the chances of attracting a mate. Like the singles-only communities that they mimic, leks are no place for families: generally of little use for feeding or bringing up young, the lek usually is abandoned by the animal once it attracts a mate or mates.

Threatening displays. An animal has to be prepared to defend its territory by fighting off invaders, but naturally it is preferable to avoid actual fighting if a mere display of strength will suffice. Fighting, after all, uses up energy and can result in injury or even death. Instead, animals rely on various threats, through vocalizations, smells, or visual displays.

The songs of birds, the drumming of woodpeckers, and the loud calls of monkeys may seem innocuous to humans, but they are all warnings that carry for long distances, advertising to potential intruders that someone else's territory is being approached. As noted earlier, many animals, such as dogs, rely on smells to mark their territories, spraying urine, leaving droppings, or rubbing scent glands around the territories' borders. Thus, an approaching animal will be warned off the territory without ever encountering the territory's defender. Or, if the invader is unfortunate enough to have trespassed on a skunk's territory, it may get a big blast of scent when it is too late to retreat.

Suppose an animal ignores these warnings, or suppose, for one reason or another, that two animals meet nose to nose at the boundaries of their respective territories. Usually there follows a threatening visual display, often involving exaggeration of the animals' sizes by the fluffing up of feathers or fur. The animals may show off their

KEY TERMS

CONDITIONING: Learning by association with particular stimuli. There are two varieties of conditioning: classical conditioning, which involves pairing a stimulus that elicits a specific response with one that does not until the second stimulus elicits a response like the first, and operant conditioning, which involves administering or withholding reinforcements (i.e., rewards) based on the performance of a targeted response.

ETHOLOGY: The study of animal behavior, including its mechanisms and evolution.

FAPs: Fixed-action patterns of behavior, or strong responses on the part of an animal to particular stimuli.

IMPRINTING: The learning of a behavior at a critical period early in life, such that the behavior becomes permanent.

INNATE: A term to describe behaviors that are present and complete within the individual and which require no experience to learn them. For example, fish have an innate ability to swim, whereas humans must learn how to walk.

NATURAL SELECTION: The process whereby some organisms thrive and others perish, depending on their degree of adaptation to a particular environment.

REFLEX: An inborn, automatic response to a stimulus by a part of an organism's body.

STIMULUS: Any phenomenon (for example, an environmental change) that directly influences the activity or growth of a living organism.

TERRITORIALITY: The behavior by which an animal lays claim to and defends an area against others of its species and occasionally against members of other species as well.

TROPISM: A response to a stimulus that acts in a particular direction, thus encouraging growth either toward or away from that stimulus.

weapons, whether claws or fangs or other devices. Or the two creatures may go through all the motions of fighting without ever actually touching, a behavior known as *ritual fighting.*

FIGHTING. The degree to which a creature engages in these displays of bravado helps define its territory. If the creature perceives that it is at the center of its own territory and is being attacked on home ground, it will go into as threatening a mode as it can muster. If, on the other hand, the animal is at the edge of its territorial boundaries, it will be much more halfhearted in its efforts at intimidation. As with humans, few animals want to fight when there is nothing really at stake. Also like humans, animals many times may seem to be spoiling for a fight without actually fighting, such that when a fight does break out, it is an aberration. This typically happens only in overcrowded conditions, when resources are scarce—again, not unlike the situation with humans.

Late in his career, Lorenz devoted himself to studying human fighting behavior. In *Das sogenannte Böse* (*On Aggression,* 1963), he maintained that fighting and warlike behavior are innate to human beings but that they can be unlearned through a process whereby humans' basic needs are met in less violent ways. Just as fighting in animal communities has its benefits, Lorenz maintained, inasmuch as it helps keep competitors separated and enables the larger group to hold on to territory, so fighting among humans might be directed toward more useful means. As discussed in Biological Communities,

it is possible that sports and business competition in the human community provides a more peaceful outlet for warlike instincts.

WHERE TO LEARN MORE

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INSTINCT AND LEARNING

CONCEPT

Among the most fascinating areas in the biological sciences is ethology, or the study of animal behavior—in particular, the areas of ethology that deal with instinct and learning. Instinct is a stereotyped, or largely unvarying, behavior that is typical of a particular species. An instinctive behavior does not have to be learned; rather, it is fully functional the first time it is performed. On the other hand, learning, in an ethological context, is the alteration of behavior as the result of experience. Clearly, the distinction between instinct and learning revolves around the question of whether an animal, in responding to a specific situation, is acting on the basis of experience or instead is guided by instincts "hardwired" within its brain. The difference would seem to be a simple one, but nothing is simple in the study of instinct and learning. Plenty of gray area exists between pure instinct and genuine learning, and within that gray area is a fascinating concept known as *imprinting,* or the learning of a behavior at a critical period early in life, such that the behavior becomes permanent.

HOW IT WORKS

Instinct

The founding fathers of ethology (the study of animal behavior, including its mechanisms and evolution) were the German zoologist Konrad Lorenz (1903–1989) and the Dutch ethologist Nikolaas Tinbergen (1907–1988). In addition to their separate contributions to the field, which we discuss later, the two scientists together developed a theory that animals employ formalized, rigid sequences of action in response to specific stimuli. These sequences they called fixed-action patterns of behavior, or FAPs.

In studying male stickleback fish, Tinbergen discovered an excellent example of a FAP. Males of that species recognize potential competitors, in the form of other stickleback males capable of breeding, by the red stripe on their underside. Tinbergen termed the red stripe a behavioral releaser, or a simple stimulus that brings about a FAP. (A stimulus is any observable fact or event that directly influences the activity or growth of a living organism.)

This particular FAP compels the male stickleback to attack anything red, even when it is not a competitor. Thus, as Tinbergen observed, jealous stickleback males actually would try to attack red British mail trucks when they could see them through the glass of their tanks. Clearly, then, a FAP such as the response to the red stripe is not something that an animal thinks through; rather, it is automatic, almost as though the animal were being acted upon, instead of acting in its own right.

There have been stories and scientific studies of animals seemingly acting above and beyond the call of duty by raising the offspring of other individuals—even those of another species. Tinbergen, for example, observed and photographed a cardinal feeding baby minnows at water's edge. Such behavior seems altruistic, touching, and even inspiring, yet for all the significance we might be inclined to place on it from our human perspective, it is nothing but a FAP. Most likely the bird had lost its own offspring, and was simply acting on a parental instinct, which caused it to respond to the sight of open, upturned, hungry mouths. It so happened that the open

mouths were not those of its offspring at all, but of fish, yet this made no difference in the behavior of the cardinal, acting as it was on an inborn, stereotypic pattern of response.

survival-friendly, controlled behavior. This is one characteristic of instinct, a concept virtually synonymous with that of the FAP: the creature acting on instinct is not thinking about what it does but is behaving almost as though it were controlled by some outside force. The use of the "outside force" concept perhaps makes instinct sound like something mystical when it is not. On the contrary, instinctive behavior is simply a survival mechanism in the brains of each member of a particular species, developed through countless generations of natural selection.

If a particular behavior helps foster the survival of a species, natural selection favors it. In other words, those individuals of a species who possess the tendency toward a particular survival-friendly behavior are the ones that survive and pass on their genes to others, while those that do not possess this tendency do not. The survival-friendly instinct may be geared toward the survival of the individual, its offspring, or others.

Closely tied to instinct is the innate animal behavior known as a reflex*:* a simple, inborn, automatic response to a stimulus by a part of an organism's body. Reflexes help animals (including humans) respond quickly to a stimulus, thus protecting them from harm. Again, the animal does not think about what it is doing. If you touch a hot stove or receive an electric shock, you do not *decide* to pull your hand back: you whip your hand away from the painful stimulus faster than you can blink. As with instinct, a reflex is a survival-friendly behavior over which the animal (in this case, you) has little control.

Innate Versus Learned Behavior

Instinct is innate, meaning that instinctive behaviors and responses are present and complete within the individual at birth. In other words, the individual does not have to undergo any experience to acquire such behaviors. For example, fish have an innate ability to swim, whereas most mammals must learn how to walk. It is fairly easy to identify innate behavior when an animal exhibits it at birth, but in some cases innate behavior manifests only later in life.

In such situations improvements in the creatures' ability to perform an innate behavior may seem to indicate that the animal is learning, when, in fact, another process is at work. For example, chickens exhibit the innate tendency toward pecking as a way of establishing and maintaining a dominance hierarchy. This is the "pecking order," to which people often refer in everyday speech as a metaphor for various hierarchies in human experience, such as those at a workplace. Though pecking is innate, chickens' ability to perform it actually improves as they grow older.

Older chickens display a better aim when pecking than do younger ones, but this does not mean that they have learned from experience. Indeed, one clue that pecking is innate in older chickens is the fact that they uniformly improve in their ability to peck. On the other hand, if they were simply learning, with practice, how to peck more accurately, one could expect that some chickens would exhibit more dramatic improvement than others, in the same way that some humans play basketball (or sing or write poetry) better than others. In fact, what has happened is that the ability to perform an innate behavior simply has improved as a result of growth: as the chickens' eyes and muscles mature, their aim improves, but this has nothing to do with experience per se.

Imprinting

This is one example of the ways in which instinctive and learned behavior can become confused, though in the pecking example there is really no gray area; rather, what is actually an innate behavior merely *seems* to be a learned one. Yet there truly is a great deal of gray area between instinct and learning. Many behaviors that at first glance might appear purely instinctive can be shown to have an experiential component—that is, an aspect of the behavior has been modified through experience or learning.

A fascinating example of how instinct and learning can be blurred or combined is imprinting, or the learning of a behavior at a critical period early in life, such that the behavior becomes permanent. Lorenz, who first developed the theory of imprinting, noted that newly hatched geese learn to walk by following their parents, but he wondered how they distinguished their parents from all other objects in their envi-



Instinct and learning can be blurred in the case of imprinting, or the learning of a behavior at a critical period early in life, such that the behavior becomes permanent. Newly hatched geese learn to walk by following their parents. If the goslings are removed from their parents, they will imprint instead on another moving object, even a human being. *(© Galen Rowell/Corbis. Reproduced by permission.)*

ronments. He discovered that if he removed the parents from view the first day after the goslings hatched and if he walked in front of the young geese at that point, they would follow him.

From these experiments, Lorenz concluded two things. First of all, during a critical period following birth, goslings follow their parents' movements and learn enough about their parents to recognize them. This critical period is short: if he walked in front of three-day old geese, they were already too old to imprint on him. Second, Lorenz determined that the parents' movement must be a behavioral releaser for imprinting; thus, if the tiny goslings happened to fix on another moving object, they would imprint on that one.

We can see in this example that imprinting has both innnate, or instinctive, *and* learned components. The tendency to imprint is innate, but if the act of imprinting itself were likewise innate, then it would be the same for all individuals within a species, and this is not the case. The vast majority of goslings will imprint on adult geese, of course, but in an experimental setting (or through some freak accident in nature), it is possible that some other object will come between the offspring and its parents, causing the offspring to imprint on it.

Once imprinting is complete, it brings about numerous consequences that are more or less automatic or inevitable. Yet for all their automatic, inevitable qualities, these consequences are not the result of innate behaviors or instincts but of learned behaviors. Thus, learning is destiny, at least to an extent. The individual's mind, at an early stage, is like wet concrete into which virtually any impression can be made. Once the individual has imprinted on something or someone, however, the concrete begins to set, and it hardens around the impressions made in it.

REAL-LIFE APPLICATIONS

Instinct at Work

When a kangaroo rat hears a rattling sound, even if that sound comes from a drum or a fan or some otherwise harmless contraption, it performs a lightning-quick escape jump maneuver. Why? Because its brain interprets the rattling sound as that of a rattlesnake ready to strike, and

it acts automatically. In other words, the kangaroo rat does not reason out a course of action; it simply moves. Nor is it acting on experience in any way: even if it has never encountered a rattlesnake, it will respond in exactly the same way.

Virtually all instinctive behavior, as we noted earlier, is geared toward preserving the life of the individual or of its offspring, and thus it serves to preserve the life of the species as well. Such is the case with the rat acting to protect itself from the snake, and so, too, with a mother when her young are threatened. People do not normally think of ducks as intimidating creatures, and in most cases they are not, but try stepping anywhere near a mother's ducklings, and watch her response. She will start to hiss, spit, and waddle forward menacingly in such a way as to terrify any would-be intruder. If the outsider is still foolhardy enough to press forward, the duck or goose will readily become a squawking, flapping, biting, pecking army of one. This behavior does not vary from mother to mother but is the same in all instances of mother ducks who perceive a threat to their ducklings—a hallmark of an instinctive action.

AUTOMATIC BEHAVIORS AND RELEASERS. There is an automatic, almost robotlike character to many an example of instinctive behavior. If an egg rolls out of a goose's nest, the goose stretches her neck until the underside of her bill touches the egg—an action that, like all instinctive ones, clearly is geared toward the survival of her offspring. Suppose someone takes the egg away while the goose is reaching for it: she continues to go through the motion of stretching to retrieve the egg. This may not seem very "smart," but, of course, instinct has nothing to do with intelligence.

Likewise, a spider preparing to lay its eggs spins a silk cocoon in a particular way, always the same and without any regard for outside factors. She begins by building a base plate, then constructs the walls of her cocoon before laying her eggs within it and sealing it with a lid. So rigid are these behavioral patterns that they cannot be altered, even if the spider needs to do so. (It is hard to imagine a spider "wanting" to do something, a term that implies decision-making abilities and a degree of self-awareness common only among higher mammals, particularly humans.)

If the spider is moved physically after she has built the base plate, she nonetheless will set about spinning walls and depositing her eggs, even though there is no base plate to hold them. The eggs, therefore, will fall out of the bottom of the incomplete web, but the spider will continue working as before, building the lid for the top. Fortunately for the spider, she has several cocoons. If she is returned to her original completed base plate as she prepares to spin the next cocoon, she will not use the base plate she already has spun; rather, like a robot, she will start from the very beginning, spinning a new base plate as though the original were not there.

Many of these automatic behaviors are triggered by a releaser. For example, a bright red spot on the bill of an adult gull serves as a releaser to its offspring, which peck on the parent's bill to obtain food. For a female rat in heat, rubbing of her hindquarters acts as a releaser for an instinctive behavior pattern known as *lordosis.* In lordosis the female flexes her front legs, lowers her torso, raises her rump, and moves the tail to one side. This posture, in turn, acts as a releaser for a male rat, who initiates copulation—yet another example of instinctive behavior as life-preserving. In this case, however, what is being preserved is not the life of an individual but of the entire species, since intercourse yields offspring.

Challenging Situations of Instinct and Imprinting

Instincts are ingrained so deeply that some animals possess what appears to be an instinct for exploiting, or taking advantage of, the instinctive behaviors of other animals. We typically think of parasites as microbes, or at least as no larger than insects, but there are species of bird regarded as parasites, inasmuch as they take advantage of other species. When people speak metaphorically of another person as a "parasite," what they really mean is that the person in question exploits the good behavior of others. A human "parasite" never has to pay for dinner at a restaurant, for instance, because he or she can count on good, decent people always to pick up the tab. Likewise, parasitic bird species, such as the North American cowbird or the European cuckoo, can rely on other species' instinctive tendency to do what all animals (and humans) should do: take care of their own offspring.

Avian parasites lay their eggs in the nest of an unwitting host and then leave, "knowing" instinctively (which is not really the same thing as knowing in the way that humans think of it)

that their victims will take care of the eggs. Cowbirds and cuckoos have developed the practice of laying their eggs in the nests of birds that are smaller than they, meaning that their hatchlings will be larger than the victims' offspring. This only adds to the detriment caused by the interlopers: since the parasites' children are larger than the hosts', this triggers a more powerful release of the host parents' instinctive feeding behavior. In other words, the parasites' offspring get more food than the hosts'. As for the parasitic adults, they are long gone, having deposited their young in the care of the hosts.

ERRORS IN IMPRINTING. The situation of the parasitic bird species is one example of the "dark side" to instinct and learning mechanisms in animals. Other examples include the many possible errors that can occur in imprinting. Such errors arise when an animal either fails to receive an imprint from an appropriate parent figure or receives an imprint from a creature of another species.

In their efforts to establish and maintain their territories and attract females, male birds of a given species learn a particular song. This takes place at a critical period when, as a nestling, the bird hears the song of its father and from this exposure eventually develops its own mature song. The process is a lengthy one: the immature bird does not begin singing until the following spring, when it starts trying to match its own, juvenile song with the one it heard from its father during the critical period.

If during that early critical period, the nestling is prevented from hearing an adult song of its own species, it never will develop a species-typical song, and thus its very life and its ability to propagate (which, in turn, affects the well-being of the entire species) are threatened. The bird may hear the songs of other species, but this does it little good. It appears that there is a strongly instinctive aspect to what the bird can learn during the critical period and also that birds are highly selective toward songs produced by other members of their species. Therefore, it learns either the right song or no song at all.

WHY IMPRINTING IS CRUCIAL

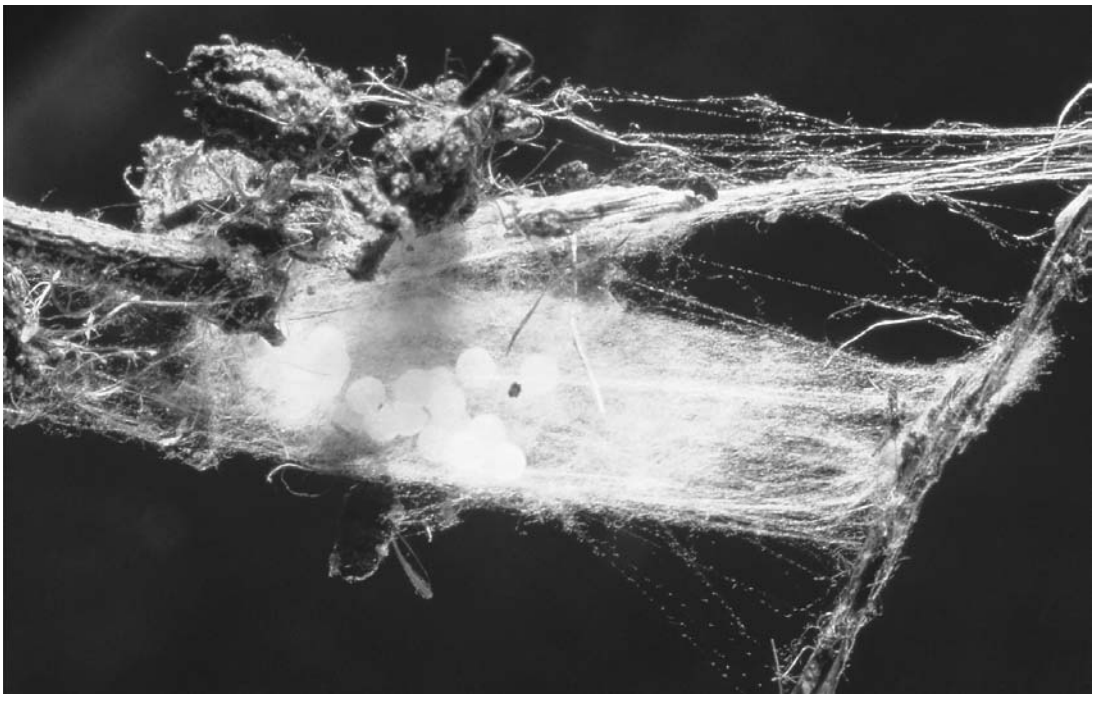
Imprinting is crucial for an animal's development and not only because the act of imprinting helps the animal learn one or another important early function, such as walking. Far beyond what happens to the animal in the first minutes of its life, imprinting will affect its entire destiny both as an individual and as a member of its species. Suppose an animal has imprinted on a creature of another species: this will haunt it for the rest of its life, for instance, determining its choice of a mate and its courtship behavior.

Many species will avoid social contact with animals that are not similar to the one to which they have imprinted. In other words, a duckling that has imprinted properly on its duck parents will want to spend time with other ducks. From the larger perspective of nature and the continuing propagation of life-forms, this is a good thing, because it helps prevent attempts to breed between different species. If, however, through some accident (or as the result of exposure to artificial conditions, such as those in an experiment), an animal has imprinted on an individual of a different species, that animal will attempt to court a member of that other species later in life—usually with disastrous results.

TARZAN THE APE MAN. In discussing the critical nature of imprinting, we could use all sorts of animal examples, some of which we have discussed. More compelling, however, is the example of a man, albeit a fictional one, who lived among the apes and attempted to become one of them. That man, of course, is Tarzan, creation of the American novelist Edgar Rice Burroughs (1875–1950). First appearing in *Tarzan of the Apes* (1914) and immortalized in countless novels, movies, comic books, and cartoons, Tarzan is the epitome of the noble savage, or the man at one with nature.

The son of an English lord, the boy is left alone as an infant in Africa after his parents die and is raised by an ape who has lost her own child. The apes name him Tarzan, which, in their language, means "white skin," and he grows up as one of them. Later, he discovers his parents' cabin and the books left there, teaches himself to read, learns English, and begins to uncover the truth of his background. As a grown man, he meets and falls in love with Jane Porter, a beautiful young American who, like his parents when he was infant, was marooned nearby after a shipboard mutiny. Jane helps expose him to civilization, and Tarzan eventually travels to France, the United States, and other far-off lands.

One can find in this astonishing tale antecedents in other rough-and-ready characters from American literature, most notably Buck, the



There is an automatic character to many examples of instinctive behavior. A spider spins a cocoon in a particular way, beginning with a base plate and then constructing walls before laying eggs and sealing the cocoon with a lid. If the spider is moved after she has built the base plate, she will continue to spin walls and deposit her eggs, leaving them to fall out the bottom of the incomplete web. *(© Science Pictures Limited/Corbis. Reproduced by permission.)*

dog turned wolf in Jack London's (1876–1916) novel *The Call of the Wild* (1903). Buck is a particularly interesting example from the standpoint of biological study, because London, an advocate of Darwin's theory of evolution by natural selection, was attempting to show the common evolutionary thread linking dog and wolf and, by inference, ape and human.

While Burroughs is not so didactic as London, he had a purpose as well, an aim opposite to that of London: to show that a human, thrust by circumstances beyond his control into a world of animals, would assert his humanness. There may even have been a class element to the Tarzan scenario, inasmuch as the young Tarzan is the offspring of nobility and ultimately proves his noble lineage by rising above his circumstances. (This, too, is a theme quite far removed from the heart of London, who was a socialist.)

All literary analysis aside, is there any truth, from the standpoint of what we know about imprinting, instinct, and learning, to Burroughs's portrayal of Tarzan? The answer is a resounding "no." Assuming that a boy could be raised by apes, he would become socialized as an ape. Appropriately enough, in one story Burroughs shows Tarzan falling in love with a female ape, thinking that he is of the same species. The ape, for her part, recognizes the difference between them and rejects the human in favor of a male ape.

A real-life Tarzan would be human only in a biological sense; otherwise, he would lack virtually all human characteristics. Not only would he be foul smelling (from our perspective) and covered with hair, but he also would be entirely ignorant of human speech or even human thought processes, which have to be learned. Most preposterous of all is the idea that he would find books and recognize them as a mode of communication, let alone teach himself to read them. Suppose that he *had* been raised as a human but that he had never seen a book or even so much as a written word. Even if he were the most brilliant human being who had ever lived, he would treat the books the way an ape would—as mere objects.

Comparing Humans and Animals

The case of Tarzan provides an appropriate place to close this discussion, with a few words on humans and their place in the context of the larg-

er concepts of instinct, imprinting, and learning. Do humans possess instincts? It appears that we do, inasmuch as we are prone to certain automatic, innate responses. For example, human babies are capable of smiling at the age of four weeks, even though they do not know what a smile "means." On the other hand, humans are not nearly as inclined to instinctive behavior as animals; in general, with higher mammals and especially humans, instinctive characteristics diminish in favor of the capacity to learn.

Our methods of learning are quite different from those of lower animals, who "learn" in ways that do not involve conscious thought. For instance, a snail will pull its head back into its shell when touched, but when it is touched repeatedly with no subsequent harm, the withdrawal response ceases. The snail has experienced habituation, a type of behavior in which an animal develops a tendency to ignore a stimulus that is repeated over and over. Apparently, the snail's nervous system has "learned" that the stimulus is not threatening and so stops the reflex.

This is a far cry from learning as humans experience it, particularly as we move past the first few weeks and months of life. Even from the earliest moments of a human's existence—that is, even in the womb—a human is self-aware in a way that few, if any, animals other than mammals are. Furthermore, the self-awareness of a human from about the age of two years old is far beyond any concept of self possessed by even the highest forms of mammal. From what we can discern, a house cat or even an ape does not experience any thought along the lines of *Who am I?* or *What is my place in the order of things?* (Of course, almost everyone who has had a pet has at one time or another believed that a cat or dog was embroiled in such types of philosophical inquiry, but this may be merely anthropomorphism—ascribing human qualities to animals.) By contrast, a two-year-old human already is forming complex judgments about his or her role with regard to Mommy, Daddy, siblings, other relatives, and household pets.

IMPRINTING IN HUMANS. Whereas humans have fewer instinctive responses than most animals and are far more capable of learning than any other creature, in the area of imprinting we are not so different from cows or even birds. We have discussed the importance of imprinting in birds, but it should be noted that

KEY TERMS

BEHAVIORAL RELEASER: A simple stimulus that brings about a fixed-action pattern of behavior, or FAP.

ETHOLOGY: The study of animal behavior, including its mechanisms and evolution.

FAPs: Fixed-action patterns of behavior, or strong responses on the part of an animal to particular stimuli. *FAP* is virtually synonymous with *instinct.*

IMPRINTING: The learning of a behavior at a critical period early in life, such that the behavior becomes permanent.

INNATE: A term to describe behaviors that are present and complete within the individual and which require no experience to learn them. For example, fish have an innate ability to swim, whereas humans must learn how to walk.

INSTINCT: A stereotyped, or largely unvarying, behavior that is typical of a particular species. An instinctive behavior does not have to be learned; rather, it is fully functional the first time it is performed.

LEARNING: The alteration of behavior as the result of experience.

NATURAL SELECTION: The process whereby some organisms thrive and others perish, depending on their degree of adaptation to a particular environment.

REFLEX: An inborn, automatic response to a stimulus by a part of an organism's body.

RELEASER: See *Behavioral releaser.*

STIMULUS: Any phenomenon (that is, an observable fact or event, such as an environmental change) that directly influences the activity or growth of a living organism.

imprinting is at least as critical among hoofed mammals, such as cattle or sheep, since they tend to congregate in large herds wherein a young animal could be separated easily from its mother. Likewise, with humans imprinting of some sort is critical.

Humans do not imprint as rigidly as geese do, but it is clear enough that some type of imprinting takes place in the mind of a baby. It is conceivable that Tarzan, having spent a year around his human parents, might retain a few human qualities—but only because it was the *first* year of his life, when the mind is by definition most impressionable. By the same token, a child that had spent six or seven years around humans would be socialized so thoroughly as a human that he or she probably would retain this human quality even if placed among apes.

From the time of the Greeks, humans have understood that part of what makes us human is contact with other humans. Therefore, an infant separated from its mother for a prolonged period during its first year of life may experience serious mental retardation; irreparable damage and even death may result from a separation of several months. There are all too many terrible stories of people who, as a result of neglect, abuse, or mere misfortune, have been forced to grow up in some form of isolation and have been stunted as a result. Usually, the outcome of this isolation is not nearly as attractive as the noble savage portrayed in literature or in such movies as *Nell* (1994), in which Jodie Foster plays a young woman who has grown up with little exposure to other humans.

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MIGRATION AND NAVIGATION

CONCEPT

Among the most intriguing aspects of animal behavior and perception is the tendency to migrate long distances, coupled with the navigational ability that makes this possible. Most such migration is seasonal, a primary example being birds' proverbial flight south for the winter. Sometimes, however, animals widely separated from their home environments nonetheless manage to find their way home. This fact has long fascinated humans, as reflected in a number of true and fictional stories on the subject that have circulated over the years. For example, *The Incredible Journey,* a 1963 Disney film remade in 1993, is a fictional tale, but there are numerous true stories of dogs and cats making their way home to their masters across thousands of miles. How do animals do this? Scientists do not fully understand the answers, but theories regarding animal navigation abound. In any case, there is no question that animals possess navigational abilities unavailable to humans, for example, echolocation, used by bats, whales, and dolphins for local navigation, requires an ability to hear sounds far beyond the range of the human ear.

HOW IT WORKS

Reasons for Migration

Why do animals migrate? Seasonal temperature changes, of course, are a factor, as in the well-known instance of birds flying south for the winter. But to justify enduring the dangers and hardships of long-distance migration, there must be an underlying cost-benefit equation whereby the benefits of migration outweigh the costs. Or, to put it another way, the physical "cost" of migrating must be less than the cost of staying home.

Human beings would perform such calculations rationally, of course, by thinking through the options and weighing them. Animals, on the other hand, rely on instinct—a word that, like many terms in science, has a somewhat different meaning within the scientific community than it does for the world at large. People tend to think of instinct as a matter of "just knowing" something, as in "I just know he/she is a good/bad person," but, in fact, instinct seems to have nothing to do with "knowing" at all.

On the contrary, instinct can be defined as a stereotyped (that is, largely unvarying) behavior that is typical of a particular species. Instinctive behavior does not have to be learned; rather, it is fully functional the first time it is performed. Though animals do exhibit some problem-solving ability, when a bird flies south for the winter, it has not thought that process through in any way. Instead, it is on "autopilot." This may seem almost magical, but it probably just reflects the processes of natural selection (see Evolution): for a particular bird species, those individuals "hard-wired" with a tendency to fly south were those that survived harsh winters, and therefore this tendency became favored in the gene pool.

Just as circumstances in the creature's home environment present a compelling need for migration, so there are other circumstances in the wintering environment that force the animal to leave as spring approaches. The wintering environment, after all, has its own native species, which most likely remain in the area even as the influx of visitors from up north arrives. Competition for food and shelter thus can become

rather intense. Over time, this increased competition creates a situation in which it is advantageous for the migrating creature to return home.

Types of Migration

The idea of birds flying south en masse for an entire winter represents only one of four different types of migration: complete, as opposed to partial, differential, or irruptive migration. Complete migration involves the movement of all individuals within a population away from their breeding grounds at the conclusion of the breeding season. Usually this entails migration to a wintering site that may be thousands of miles away.

Some species practice partial migration, whereby some individuals remain at the breeding ground year-round, while others migrate. Others employ differential migration, in which all members of the population migrate, but for periods of time and over distances that vary as a function of age or sex. For example, herring gulls migrate for increasingly shorter distances the older they get, and male American kestrels remain at the breeding grounds longer than females. Even when the male birds do set out on their journeys, they do not travel as far as their female counterparts. Finally, there is irruptive migration, whereby certain species do not migrate at all during some years but may do so during other years. The likelihood of migration seems to be tied to climate and resource availability: the colder the winter and the more scarce the food, the more likely migration will occur in species prone to irruptive migratory behavior.

Directions of Migration

Though southward migration is the most widely known form of migratory behavior, not all migration is from the north to the south. Actually, this type of movement is more properly called *latitudinal migration,* since it also takes place in the Southern Hemisphere, where, of course, it is from south to north. (Also, winter in those latitudes occurs at the same time as summer in the Northern Hemisphere.) There is far less habitable land below the equator than above it, however, so latitudinal migration in the Southern Hemisphere is not nearly as significant as it is at northerly latitudes.

There are, in fact, species of bird, such as the prairie falcon (*Falco mexicanus*), that travel longitudinally, or from east to west. This type of movement probably is related to seasonal changes in the location, availability, and choice of prey. Nor does all migration involve movements across Earth's surface; there is also elevational migration, which entails a change of altitude or depth beneath the sea.

Animals that live on mountains, for instance, may take part in elevational migration, moving to lower elevations in winter just as other species move to lower latitudes. For zooplankton, tiny animals that float on the waters of the open ocean, migration is a matter of changing depths in the water. During the summertime, when populations of zooplankton are large, these organisms live on the surface and feed on the plant life there. During the cold months, however, zooplankton migrate to depths of about 3,300 ft. (1 km) and do not feed at all.

Real-Life Applications

The Process of Migration

When animals migrate, they move along more or less the same corridors or paths each year. For North American birds migrating south for the winter, one of the most commonly used "flyways" is across the Gulf of Mexico, a journey of 500-680 mi. (800–1,000 km). To make it across the open waters of the gulf, birds have to store up fat, on which they can live for some time while out of sight of food sources.

Migrating birds are not like the proverbial parent (usually a father) who will not let the children stop to go to the bathroom on a long road trip. As they make their way south, birds stop regularly to rest and eat, sometimes for days at a time. These stops are particularly frequent and long just before crossing a large expanse of water. Only when the bird has stored sufficient quantities of body fat does it resume the journey.

Day and night travel. In North America it is common to see flocks of birds apparently flying south during the daytime in the autumn months. Yet most migrating bird species travel at night. The fewer species that travel by day tend to follow paths that are slower and less direct than those of nocturnal migrants. The reason for this difference has to do with the differences in feeding opportunities.



Birds are not the only creatures capable of great navigational feats. Salmon come back from the oceans and fight their way upstream to spawn in the very same spot at which they were hatched. *(© Ralph A. Clevenger/Corbis. Reproduced by permission.)*

Nocturnal migrants have the entire day in which to rest, forage for food, and eat, thus building up reserves of energy for the nonstop flight that night. Daytime migrants, on the other hand, have to forage at the same time that they are traveling. For this reason, they tend to stick close to the coastlines, which offer abundant supplies of insect life. This slows them down but offers a dependable food supply.

Feats of Navigation

In making their journeys, some creatures display navigational skills that would put such great mariners as Ferdinand Magellan and James Cook to shame. For example, the arctic tern (*Sterna paradisaea*) is a complete migrant in every sense of the word. Not only does the tern engage in complete migration, as defined earlier, but it also literally crosses the globe from pole to pole. In traveling from the Arctic to the Antarctic and back again in a single year, the arctic term completes a round-trip migration of more than 21,750 mi. (35,000 km). This distance, nearly the circumference of the planet, is the longest regular migratory path of any animal.

A specimen of another bird species, the Manx shearwater, was taken via airplane to Boston from its home on an island off the coast of Wales. Released experimentally in Boston, the bird took only 13 days to return to its point of origin, a flight of some 3,050 mi. (4,880 km). In another experiment, an albatross from Midway Island, deep in the Pacific, was released in the Philippines and made its way to its home area, a distance of 4,120 mi. (6,592 km), in only 32 days. There are also many examples of swallows finding their way across great distances. For instance, swallows that winter in southern Africa still manage to get back to their homes in northern Europe each spring. Then there are the swallows of San Juan Capistrano, southwest of Los Angeles, which leave every year on October 23 and return like clockwork on March 19.

Birds are not the only creatures capable of such great navigational feats. Monarch butterflies (*Danas plexippus*), which are born in Canada or the northern United States, winter each year in southern California, just as they have done for countless years. Then, when winter is over, they make their way back to their home regions. Likewise, salmon come back from the oceans and fight their way upstream to spawn in the very same spot at which they were hatched.

How Do They Do It?

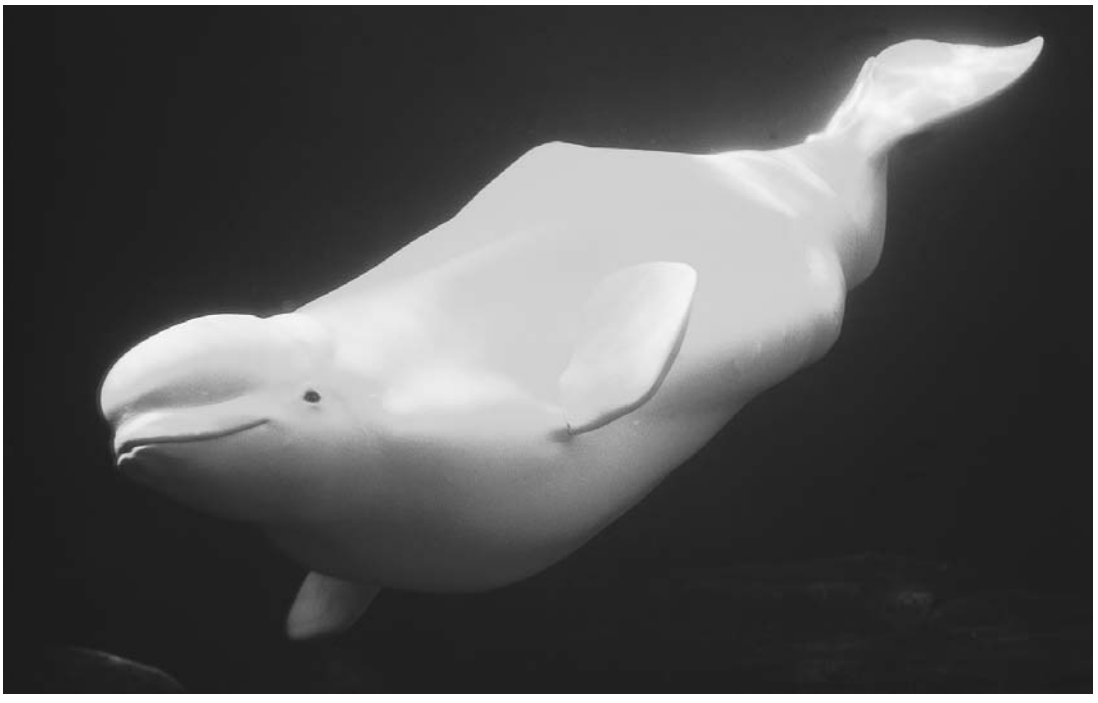
Based on these and other examples, one is left wondering, how do they do it? Numerous observations and theories have been put forward to answer this question. Salmon, for instance, seem to distinguish their home streams on the basis of smell, whereas some birds appear to use visual signals, primarily the position of the Sun or star patterns. Auditory cues and the sensitivity of migratory species to these cues often have been advanced as a key to migration behavior. Finally, one theory, which we discuss shortly, holds that sensitivity to Earth's magnetic field provides long-distance travelers with the navigational aid they need.

Several experiments have been performed on a variety of creature well known for its navigational abilities: the homing pigeon, which often can return across many hundreds of miles to its home. While they are undergoing training by humans, these pigeons are released from a series of sites, each just a little farther from the birds' home area. This training seems to make them accustomed to traveling long distances and to finding their way back. Thus, once trained, a pigeon released 100 mi. (63 km) or more from its home will begin flying in the correct direction within a few minutes.

Biological clocks and navigation. Several theories regarding pigeons' homing skills cite internal or biological clocks (see Biological Rhythms). One such theory, which is no longer accepted widely, held that the pigeon's perception of the Sun's position in the sky, combined with its biological clock, helped it navigate. Experiments have not proved this to be the case, however.

In one such trial pigeons were kept in a laboratory from which they could see the Sun for only very limited periods of time each day. After an extended period, the pigeons, with their eyes covered, were taken away about 40 mi. (64 km) to the south and released, so that the moment of release was their first unobstructed view of the Sun in weeks. Assuming the theory was correct, the pigeons would have been disoriented, but, in fact, they quickly took stock of their position and began flying north.

"Magnetic maps." One intriguing theory of animal navigation holds that creatures carry in their brains "magnetic maps," or strong sensitivities to Earth's magnetic field, that assist them in finding their way across distances. As reported in *National Geographic Today* on-line (October 12, 2001), research on loggerhead turtles has shown that hatchlings are sensitive to the strength and direction of Earth's magnetic field and apparently use this in their migratory navigation.



A fascinating example of animal navigation is echolocation, which is not necessarily tied to migration. Rather, it provides a means of local navigation—and escape from predators—for creatures that lack the ability to see in their environments, such as this whale in the cloudy realm of the ocean. *(© Terry Whittaker. Photo Researchers. Reproduced by permission.)*

By rigging up harnesses attached to electronic tracking units and outfitting the turtles with these devices, researchers were able to follow the course of their migration. Because these are, after all, turtles (though seaborne rather than terrestrial or land-based), migration is no speedy affair. To complete the trip, an 8,000-mi. (12,900-km) circuit from south Florida around the Saragasso Sea in the north Atlantic and back again, takes 5–10 years.

In the experiment, baby loggerheads were tagged with tracking systems just after they came out of their underground nests on the eastern coast of Florida. Still babies, they would normally begin a journey across the Atlantic, past the Canary and Cape Verde islands on the west coast and Africa and then back to Florida. But instead of going on this journey, the turtles in the experiment were placed in a large circular water tank surrounded by an electric coil capable of generating specific magnetic fields.

By turns, the research team exposed the animals to fields simulating those in three key spots along the route: northern Florida, the area off the coast of Portugal, and the region near the Cape Verde Islands. In each case, turtles responded to these magnetic stimuli by turning in the appropriate direction—for instance, south when they perceived that they were in the magnetic field equivalent to that of Portugal and west in the field resembling that of Cape Verde.

The research team, which published its results in the distinguished journal *Science,* concluded that the turtles were hardwired with magnetic sensitivities. The team leader Kenneth Lohmann, a biologist at the University of North Carolina in Chapel Hill, told *National Geographic Today,* "These turtles have never been exposed to water, yet they were able to process magnetic information and change their swimming direction accordingly. It seems they inherited some sort of magnetic map."

Echolocation

One final, fascinating example of animal navigation is echolocation, which differs from most of the navigational behaviors we have discussed so far in that this one is not necessarily tied to migration. Rather, echolocation provides a means of local navigation for creatures that lack the ability to see in their environments: bats flying through caves and dolphins, porpoises, and

KEY TERMS

BIOLOGICAL CLOCK: A mechanism within an organism (for example, the pineal gland in the human brain) that governs biological rhythms.

ECHOLOCATION: The use of sound waves, which are reflected back to the emitter, as a means of navigating.

INSTINCT: A stereotyped, or largely unvarying, behavior that is typical of a particular species. An instinctive behavior does not have to be learned; rather, it is fully functional the first time it is performed.

MIDDLE EAR: A small cavity that transmits sound waves, via a network of tiny bones, from the eardrum, which lies between it and the outer ear. Bats use the middle ear to separate transmission and reception signals in echolocation.

MIGRATION: A pattern of movement, usually regular and seasonal, whereby animals travel (typically guided by instinct) to specific locations.

NATURAL SELECTION: The process whereby some organisms thrive and others perish, depending on their degree of adaptation to a particular environment.

toothed whales swimming beneath the ocean's surface.

The frequency of a sound is related not to volume but to pitch: the higher the note, the higher the frequency. The frequency is measured in Hertz, or cycles per second. Human beings are capable of hearing sounds between 20 Hz and 20,000 Hz, whereas cats can hear sounds up to 32,000 Hz and dogs up to 46,000 Hz. This is why these creatures can hear dog whistles and other sounds inaudible to humans. Even the hearing ability of these household pets pales compared with that of bats and oceangoing mammals, which can hear tones up to 150,000 Hz.

Echolocation represents an evolutionary triumph in the form of adaptation to environments—the dark, nocturnal world of the bat and the cloudy realm of sea mammals. In the distant past, bats that hunted for insects during the day would have been at a disadvantage compared with birds, which are nimble of movement and extremely sharp-eyed in spotting their insect prey. Whales, porpoises, and dolphins were in an even worse situation with regard to sharks. Sharks, known for a finely tuned sense of smell, were not only competitors for prey but, as tertiary consumers (see Food Webs), they were and are also potential predators of sea mammals.

IN BATS. Only certain kinds of bats use echolocation. These are the carnivorous varieties that live on frogs, fish, and insects, as opposed to the herbivorous eaters of fruit and nectar. These carnivorous bats fly through the darkness, emitting extremely high frequency sounds and receiving the echoes from these sounds. Contained in the echo is a whole database of information regarding the object off which it has reflected: its distance, direction, size, surface texture, and even material composition.

Interestingly, the volume of these sounds is so great—as high as 100 decibels (dB)—that if people were able to hear them, the noises would be almost literally ear-splitting. (The upper range of safety is 120 dB.) As it is, a person would hear only clicks or chirps. Scientists have long wondered how the bats can both emit these sounds, which would be deafening to the bat, and hear them at the same time. Experimental evidence indicates that when the bat emits a sound, the middle ear (that is, the middle portion of the ear's interior) adjusts in such a way as to momentarily deafen the bat. A split second later, the bat's inner ear readjusts so as to permit it to hear the echo from the previous sound.

IN OCEANGOING MAMMALS. It is true, as the tagline for the 1979 film *Alien* threatened, that "In space no one can hear you scream." Another way of putting this is that sound requires a material medium through which to travel, and the more dense the medium, the more efficiently it moves. Thus, sound moves more effectively through water than through air, and for this reason echolocation is even more

suited to the deep-sea environment than it is to the world above ground.

As with bats, undersea mammals send out sounds and then listen for the echoes. Owing to their heightened sense of hearing, these creatures obtain far more information from sounds than a human would. Sound, in fact, does for them what sight would do for a human, providing a detailed, three-dimensional image of their surroundings, but the images it offers are even more precise because sound waves are less subject to interference and diffraction than light waves. (For example, sound waves can simply go around a building, whereas the light waves that hit one side of a building are not visible from the other side.)

Toothed whales, dolphins, and porpoises, all of which normally would be disadvantaged by their weak senses of sight and smell, use more or less the same means to navigate by echolocation. A fatty deposit in the mammal's head helps it direct the sound; then an area of the lower jaw called the *acoustic window* receives reflected noises. A fatty organ in the middle ear transmits vibrations from the echo, which are translated into neural impulses that go to the brain.

As with the bat, the toothed whale has special structures in its head that help it hear even as it sends out noises. Some species have bony insulating structures, which separate the portion of the head where sounds are received from that part where sounds are generated. Likewise, structures in the middle ear assist the whale in distinguishing whether sounds come from the left or the right, thus facilitating the whale's navigation.

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THE BIOSPHERE AND ECOSYSTEMS

THE BIOSPHERE

ECOSYSTEMS AND ECOLOGY

BIOMES

THE BIOSPHERE

CONCEPT

The biosphere is simply "life on Earth"—the sum total, that is, of all living things on Earth. Yet the whole is more than the sum of the parts: not only is the biosphere an integrated system whose many components fit together in complex ways, but it also works, in turn, in concert with the other major earth systems. The latter include the geosphere, hydrosphere, and atmosphere, through which circulate the chemical elements and compounds essential to life. Among these elements is carbon, a part of all living things, which also cycles through the nonliving realms of soil, water, and air—just one of many vital biogeochemical cycles. As for the compounds on which life depends, none is more important than water, which, though it is the focal point of the hydrosphere, passes through the various earth systems as well. Organisms participate in the hydrologic cycle by providing moisture to the air through the process of transpiration, and they likewise benefit from the downward movement of moisture in the form of precipitation. These and many other interactions make it easy to see why scientists speak of Earth as a system—and why some go even further and call it a living thing.

HOW IT WORKS

Earth Systems

Chances are that the mention of the word *system* calls to mind something mechanical or electrical, produced by humans: for example, a heating and cooling system. This application of the word is close to the scientific meaning, but in the sciences *system* identifies a wider range of examples. In scientific terms a system is any set of interactions that can be set apart mentally from the rest of the universe for the purposes of study, observation, and measurement. Thus, virtually by definition, a system is something in which the various parts fit together harmoniously, as though they were designed—or adapted over millions of years—to do so.

Anything outside the system is known as the *environment,* and numerous qualifying terms identify the level of interaction between the system and its environment. An isolated system is one so completely sealed off from its environment that neither matter nor energy passes through its boundaries. This is a merely theoretical construct, however, because, in practice, some matter *always* flows between system and environment. For example, regardless of how tightly a vault or other interior chamber is sealed, there is always room for matter at the microscopic or atomic level to pass through the barrier; moreover, energy, which in many forms does not require any material medium for its transmission, will pass through as well.

Earth itself is an approximation of a closed system, or a system in which, despite the sound of its name, exchanges of energy (but not matter) with the environment are possible. Earth absorbs electromagnetic energy from the Sun and returns that energy to space in a different form, but very little matter enters or departs Earth's system. Earth is not a perfectly closed system, however, since meteorites can enter the atmosphere and hydrogen can escape. Without the intrusion of meteorites, in fact, it is unlikely that life could exist on the planet, because these projectiles from space first brought water (and possibly even the carbon-based rudiments of life) to the planet Earth more than four billion years ago.

Nevertheless, Earth more closely resembles a closed system than it does an open system, or one that allows the full and free exchange of both matter and energy with its environment. The human circulatory system is an example of an open system, as are the various "spheres" of Earth (geosphere, hydrosphere, biosphere, and atmosphere) that we discuss later in this essay. The distribution of matter and energy within these earth systems may vary over time, but the total amount of energy and matter within the larger earth system is constant.

THE FOUR "SPHERES." On the other hand, the four subsystems, or "spheres," within the larger Earth system are very much open systems. Of these four subsystems, the name of only one, the atmosphere, is familiar from everyday life, whereas those of the other three sectors (geosphere, hydrosphere, and biosphere) may sound at first like scientific jargon. Yet each has a distinct identity and meaning, and each represents a part of Earth that is at once clearly defined and virtually inseparable from the rest of the planet.

The geosphere is the upper part of the planet's continental crust, the portion of the solid earth on which human beings live and which provides them with most of their food and natural resources. It is also the oldest, followed by the hydrosphere, which had its beginnings with several hundred millions years' worth of rains that took place about four billion years ago. Today the hydrosphere includes all water on Earth, except for water vapor in the atmosphere. The latter, incidentally, was probably the last of the four subsystems to take shape: though Earth in its early stages had a blanket of gases around it, there was no oxygen. (See Paleontology for more about the early atmosphere, oxygen, and early life.)

THE ATMOSPHERE. Today the atmosphere is 78% nitrogen, 21% oxygen, and 0.93% argon. The remaining 0.07% is made up of water vapor, carbon dioxide, ozone (a form of oxygen in which three oxygen atoms bond chemically), and noble gases. The noble gases, including argon and neon, are noted for their lack of reactivity, meaning that they are extremely resistant to chemical bonding with other elements.

Nitrogen also tends to be unreactive, and the reason for its abundance in the atmosphere lies in the fact that it never attempted to bond with other elements. Therefore, nitrogen, along with the noble gases, is simply "hanging in the air" (literally), left over from the time when volcanoes hurled it into the atmosphere several billion years ago. By contrast, oxygen (both in O_2 and O_3, or ozone, molecules) and the other elements in air are vital to life. Furthermore, oxygen is one of two elements, along with hydrogen, that goes into the formation of water.

OVERLAP BETWEEN SUBSYSTEMS. The present atmosphere would not exist without the biosphere. In order to put oxygen into the air, there had to be plants, which take in carbon dioxide and release oxygen in the process of photosynthesis. This resulted from an exceedingly complex series of evolutionary developments from anaerobic, or non-oxygen-breathing, single-cell life-forms to the appearance of algae. As plant life evolved, eventually it put more and more oxygen into the atmosphere, until the air became breathable for animal life. Thus, the atmosphere and biosphere have sustained one another.

Such overlap is typical and indeed inevitable where the open earth subsystems are concerned, and examples of this overlap are everywhere. For instance, plants (biosphere) grow in the ground (geosphere), but to survive they absorb water (hydrosphere) and carbon dioxide (atmosphere). Nor are plants merely absorbing: they also give back oxygen to the atmosphere, and by providing nutrition to animals, they contribute to the biosphere. At the same time, the many components of the picture just described are involved in complex biogeochemical cycles, which we look at later.

THE BIOSPHERE IN CONTEXT. The biosphere is, of course, integral to the functioning of earth systems. First of all, the present atmosphere, as we have noted, is the product of respiration on the part of plants, which receive carbon dioxide and produce oxygen. In addition, transpiration, a form of evaporation from living organisms (primarily plants), is a mechanism of fundamental importance for moving moisture from the hydrosphere through the biosphere to the atmosphere.

We examine transpiration later, within the larger context of evapotranspiration, along with another area in which the biosphere interacts closely with one or more of the other earth systems: soil. Though soil is part of the geosphere, its production and maintenance is an achievement of all spheres. The role of the biosphere in this

instance is particularly important: the amount of decayed organic material (i.e., dead plants and animals) is critical to the quality of the soil for sustaining further life in the form of plants and other organisms that live underground.

As important as the biosphere is, it may be surprising to learn just what a small portion of the overall earth system it occupies. As living beings, we tend to have a bias in favor of the living world, but the overwhelming majority of the planet's mass and space is devoted to nonliving matter. The geosphere alone accounts for almost 82% of the combined mass of the four subsystems. (This is *not* the combined mass of Earth, which would be much larger; remember that the geosphere is only the extreme upper layer of Earth, and does not include the vast depths of the lower mantle and core.)

Of the remaining mass that makes up the four earth systems, the hydrosphere is a little more than 18%, the atmosphere less than 1%, and the biosphere a tiny 0.00008%. Note just how much greater the amount of mass is in the air, which we tend to think of as being weightless (though, of course, it is not), than in the biosphere. Even within the biosphere's almost infinitesimal fraction of total mass, the animal kingdom accounts for less than 2%, the remainder being devoted to other kingdoms: plants, fungi, monera (including bacteria), and protista, such as algae. (See Taxonomy and Species for more about the kingdoms of living things.) It need hardly be added that humans, in turn, are a very, very small portion of the animal world.

Water and the Hydrologic Cycle

As any backyard horticulturist knows, plants need good soil *and* water. In the course of circulating throughout Earth, water makes its way through organisms in the biosphere as well as reservoirs housed within the geosphere. It also circulates continuously between the hydrosphere and the atmosphere. This movement, known as the hydrologic cycle, is driven by the twin processes of evaporation and transpiration.

The first of these processes, of course, is the means whereby liquid water is converted into a gaseous state and transported to the atmosphere, while the second one—a less familiar term—is the process by which plants lose water through their stomata, small openings on the undersides of leaves. Scientists usually speak of the two as a single phenomenon, evapotranspiration. The atmosphere is just one of several "compartments" in which water is stored within the larger environment. In fact, the atmosphere is the only major reservoir of water on Earth that is not considered part of the hydrosphere.

ACCOUNTING FOR EARTH'S WATER SUPPLY. The water that most of us see or experience is only a very small portion of the total. Actually, that statement should be qualified: the oceans, parts of which most people have seen, make up about 5.2% of Earth's total water supply. This may not sound like a large portion, but, in fact, the oceans are the second-largest water compartment on Earth. If the oceans are such a small portion yet rank second in abundance, two things are true: there must be *a lot* of water on Earth, and most of it must be in one place.

In fact, the vast majority of water on Earth is stored in aquifers, or underground rock formations, that hold 94.7% of the planet's water. Thus, deep groundwater and oceans account for 99.9% of the total. Glaciers and other forms of permanent and semipermanent ice take third place, with 0.065%. Another 0.03% appears in the form of shallow groundwater, the source of most local water supplies. Next are the inland surface waters, including such vast deposits as the Great Lakes and the Caspian Sea as well as the Mississippi-Missouri, Amazon, and Nile river systems and many more, which collectively make up just 0.003% of Earth's water.

ATMOSPHERIC MOISTURE AND WEATHER. That leaves only 0.002%, which is the proportion taken up by moisture in the atmosphere: clouds, mist, and fog, as well as rain, sleet, snow, and hail. While it may seem astounding that atmospheric moisture is such a small portion of the total, this fact says more about the vast amounts of water on Earth than it does about the small amount in the atmosphere. That "small" amount, after all, weighs 1.433×10^{13} tons (1.3×10^{13} tonnes), or 28,659,540,000,000,000 pounds (12,999,967,344,000,002 kg).

This moisture in the atmosphere is the source of all weather, which clearly has an effect on Earth's life-forms. (Weather is the condition of the atmosphere at a given time and in a given place, whereas climate is the pattern of weather in a particular area over an extended period of

time.) On the one hand, rain is necessary to provide water to plants, and desert conditions can sustain only very specific life-forms; on the other hand, storms, icy precipitation, and flooding can be deadly.

Biogeochemical Cycles

Water is not the only substance that circulates through the various earth systems. So, too, do six other substances or, rather, chemical elements. These elements are composed of a single type of atom, meaning that they cannot be broken down chemically to make a simpler substance, as is the case with such compounds as water. The six elements that cycle throughout Earth's systems are hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur. The two following lists provide rankings for their abundance. The first shows their ranking and share in the entire known mass of the planet, including the crust, living matter, the oceans, and atmosphere. The second list shows their relative abundance and ranking in the human body.

Abundance of Selected Elements on Earth (Ranking and Percentage):

- 1. Oxygen (49.2%)
- 9. Hydrogen (0.87%)
- 12. Phosphorus (0.11%)
- 14. Carbon (0.08%)
- 15. Sulfur (0.06%)
- 16. Nitrogen (0.03%)

Abundance of Selected Elements in the Human Body (Ranking and Percentage):

- 1. Oxygen (65%)
- 2. Carbon (18%)
- 3. Hydrogen (10%)
- 4. Nitrogen (3%)
- 6. Phosphorus (1%)
- 9. Sulfur (0.26%)

Note that the ranking of all these elements (with the exception of oxygen) is relatively low in the total known elemental mass of Earth, whereas their relative abundance is much, much higher within the human body. This is significant, given the fact that these elements are all essential to the lives of organisms. All six of these elements take part in biogeochemical cycles, a term used to refer to the changes that a particular element undergoes as it passes back and forth through the various earth systems and particularly between living and nonliving matter.

The carbon and nitrogen cycles. Carbon, for instance, is present in all living things and is integral to the scientific definition of the word *organic.* The latter term does not, as is popularly believed, refer only to living and formerly living things, their parts, and their products, such as sweat or urine. Organic refers to the presence of compounds containing carbon and hydrogen. The realm of organic substances encompasses not only the world of the living, the formerly living, and their parts and products, but also such substances as plastics that have never been living.

The carbon cycle itself involves movement between the worlds of the living and nonliving, the organic and inorganic. This highly complex biogeochemical cycle circulates carbon from soil and carbonate rocks (which are inorganic because they do not contain carbon-hydrogen compounds) to plants and hence to animals, which put carbon dioxide into the air. Likewise, the nitrogen cycle moves that element among all these reservoirs.

Because nitrogen is highly unreactive, the participation of microorganisms in the nitrogen cycle is critical to moving that element between the various earth systems. These organisms "fix" nitrogen, meaning that by processing the element through their bodies, they bring about a chemical reaction that makes nitrogen usable to plant life. Additionally, detritivores and decomposers in the soil are responsible for transforming nitrites and nitrates (compounds of nitrogen and oxygen) from the bodies of dead animals into elemental nitrogen that can be returned to the atmosphere.

Real-Life Applications

Soil and the Life in It

The soil is a sort of anchor to the biosphere. It teems with life like few other areas within the earth system, and, indeed, there are more creatures—plant, animal, monera, protista, and fungi—living in the soil than above it. Minerals from weathered rock in the soil provide plants with the nutrients they need to grow, setting in motion the first of several steps whereby organisms take root in and contribute to the soil.



Numerous ant species perform a positive function for the environment. Like earthworms, they aerate soil and help bring oxygen and organic material from the surface while circulating soils from below. *(© Ralph A. Clevenger/Corbis. Reproduced by permission.)*

Plants provide food to animals, which, when they die, likewise become one with the soil. So, too, do plants themselves. Organisms from both the plant and animal kingdoms leave behind material to feed such decomposers as bacteria and fungi, which, along with detritivores, are critical to the functioning of food webs (see entry). Detritivores, of which earthworms are a great example, are much more complex organisms than the typically single-cell decomposers.

We cannot see bacteria, but almost anyone who has ever dug in the dirt has discovered another type of organism: the Annelida phylum of the animal kingdom, which includes all segmented worms, among them, the earthworm. (Incidentally, the leech family also falls within phylum Annelida.) These slimy creatures at first might seem disgusting, but without the appropriately named earthworm, our world could not exist as it does.

Detritivores consume the remains of plant and animal life, which usually contain enzymes and proteins far too complex to benefit the soil in their original state. By feeding on organic remains, detritivores cycle these complex chemicals through their internal systems, thus causing the substances to undergo chemical reactions that result in the breakdown of their components. As a result, simple and usable nutrients are made available to the soil.

Earthworms, which are visible and relatively large, are not the only worms at work in the soil. There are also the colorless creatures of the phylum Nematoda, or roundworms. Included in this phylum are hookworms and pinworms, which can be extremely detrimental to the body when they live inside it as parasites. (See Parasites and Parasitology.) This is one good reason (among many) not to eat dirt. But nematodes in the soil, most of them only slightly larger than microorganisms, perform the vital function of processing organic material by feeding on dead plants. Even in a soil situation, however, some nematodes are parasites that live off the roots of such crops as corn or cotton.

In addition to earthworms, ants and other creatures are also significant inhabitants of the soil. Like earthworms, ants aerate soil and help bring oxygen and organic material from the surface while circulating soils from below. Among the larger creatures that call the soil home are moles, which live off earthworms, grubs (insect larvae), and the roots of plants. By burrowing under the ground, they help to loosen the soil,

making it more porous and thus receptive to both moisture and air. Other large burrowing creatures include mice, ground squirrels, and, in some areas, even prairie dogs.

Soils and the Environments They Help Create

Five different factors determine the quality of soil: parent material (the decayed organisms and weathered rock that make it up), climate, the presence of living organisms, topography (the shape of the land, including prominent natural features), and the passage of time. These factors influence the ability of the soil to sustain life.

For example, in a desert, a place that obviously has a smaller abundance and complexity of life-forms (see Biological Communities), the soil itself is lacking in this life-sustaining quality. Desert soil, in fact, is usually referred to as *immature* soil. Healthy soil normally has a deep A horizon, the area in which decayed organic material appears and atop which humus sits. In general, the deeper the A horizon, the better the soil. Immature soil, on the other hand, has a very thin A horizon and no B horizon, which is the subsoil that typically separates the A horizon from a layer of weathered material that rests even lower, at the C horizon just above bedrock.

In deserts, by definition, the water supply is very limited, and only those species that require very little water—for example, the varieties of cactus that grow in the American Southwest—are able to survive. But lack of water is not the only problem. Desert subsoils often contain heavy deposits of salts, and when rain or irrigation adds water to the topsoil, these salts rise. Thus, watering desert topsoil actually can make it a worse environment for growth.

Tropical rain forests. The soil in rain forests has just the opposite problem of desert soil: instead of being immature, it has gone beyond maturity and reached old age, a point at which plant growth and water percolation (the downward movement of water through the soil) have removed most of its nutrients. In environments located near the equator, whether these regions be desert or rain forest, soils tend to be "old." This helps to explain the fact that equatorial regions are usually low in agricultural productivity, despite the fact that they enjoy an otherwise favorable climate.

Given the poor quality of equatorial soil, one might wonder how it is that some of the most lush rain forests are located in the equatorial regions of Africa and South America. The answer is that a rain forest has such a wide assortment of life-forms that there is never a shortage of decayed organic material to "feed" the soil. Due to the sheer breadth and scope of the rain forest's ecological diversity, there are bound to always be plants and animals dying, replenishing what would otherwise be poor soil. The rapid rate of decay common in warm, moist regions (which are extremely hospitable to bacteria and other microbes) further supports the process of renewing minerals in the ground.

The fact that decayed organic material is critical to the life of soil helps to explain why many environmentalists have long been concerned about the destruction of tropical rain forests. For example, in Brazil, vast portions of the Amazon rain forest have been clear-cut, subjected to an extremely destructive form of slash-and-burn agriculture that is motivated by modern economic concerns—the desire of the country's leaders to create jobs and exports—but which resembles practices applied (albeit on a much smaller scale) by premodern peoples in Central and South America.

By removing the heavy jungle canopy of tall trees, clear-cutting exposes the ground to the heat of the Sun and the pounding of monsoon rains. Sun and rain, thanks to the removal of this protection, fall directly on the ground, parching it in the first instance and eroding it in the second. Furthermore, when trees and other vegetation are removed, the animal life that these plants supported disappears as well, and this has a direct impact on the soil by removing organisms whose waste products and bodies eventually would have decayed and enriched it.

What makes good soil? The soil of the Brazilian rain forest may be old and weak, but thankfully there are places in the world where the soil tells an entirely different story. Instead of being nutrient-poor, this soil is nutrient-rich, and instead of being red, such soil is a deep, rich black. Sometimes regions of good and bad soil exist in close proximity, as in ancient Egypt, where the Nile made possible a narrow strip of extraordinarily productive land, running the length of the country, flanked by deserts. The latter the Egyptians called "the red land" because

of its nutrient-poor soil, whereas their own fertile region was "the black land."

Just as Egypt, after its annexation by the Romans in 30 B.C., became known as the breadbasket of the Roman Empire, there are other "black lands" that serve as the breadbaskets of today's world. Unlike Egypt, however, most are located in temperate rather than equatorial regions. (See Biomes for more about temperate regions.) Examples include the midwestern United States, western Canada, and southern Russia, regions characterized by vast plains of fertile black soil. Below this rich topsoil is a thick subsoil that helps hold in moisture and nutrients.

Rivers such as the Nile, the Mississippi-Missouri, or the Volga in Russia make possible the richest variety of soil on Earth, alluvial soil, a youngish sediment of sand, silt, and clay. A river pulls soil along with it as it flows, and with this comes nutrients from the regions through which the river has passed. The river then deposits these nutrients in the alluvial soil at the delta, the area where it enters a larger body, usually of salt water. (A delta is so named because, as it widens in the region near the sea, the shape of the river is like that of the Greek letter delta, or Δ.)

Because they are depositories for accumulated alluvial soil, delta regions such as Mississippi and Louisiana in the United States (where the mighty Mississippi-Missouri, the largest river system in North America, empties into the Gulf of Mexico), are exceedingly fertile. The same is true in the Volga and Nile deltas, the deltas of the Danube and other major European rivers, and those of lesser-known rivers in Canada or Australia.

FERTILIZER. It is also possible to artificially improve soil that is not in a river delta, or that has not otherwise been blessed by nature. The most significant way to achieve this is by using fertilizer, which augments the nutrients in the soil itself. As noted earlier, nitrogen is highly nonreactive, meaning that it tends not to bond chemically with other substances. However, because it is a necessary component of biogeochemical cycles, it is critical that nitrogen be introduced to the soil in such a way that it becomes useful, and typically this is done by combining it with a highly reactive element: oxygen.

Fertilizers may contain nitrogen in the form of a nitrate, which is a compound of nitrogen and oxygen, or they may include a nitrogen–hydrogen compound. The latter may be ammonia (NH_3) or ammonium (NH_4^+). Note that ammonia is much more than the product with which it is most readily associated: a household cleaner. In fact, ammonia is an extremely abundant substance, occurring naturally, for instance, in the atmospheres of Venus and other planets in our solar system. The importance of ammonia is reflected by the fact that it and water are the only two substances that chemists regularly refer to by their common names, as opposed to a scientific name such as carbon dioxide.



DESERT TORTOISE AND BEAVERTAIL CACTUS IN THE MOJAVE DESERT. ONLY THOSE PLANT AND ANIMAL SPECIES THAT CAN ENDURE A LIMITED WATER SUPPLY AND IMMATURE SOIL WITH HEAVY DEPOSITS OF SALT IN THE LOWER LAYERS CAN SURVIVE A DESERT ENVIRONMENT. *(© D. Suzio. Reproduced by permission.)*

As for ammonium, its extra hydrogen atom makes it a substance that dissolves in water and is attracted to negatively charged surfaces of clays and organic matter in soil. Therefore, it tends to become stuck in one place rather than to move around, as nitrate does. Plants in acidic soils typically receive their nitrogen from ammonium, but in nonacidic soils, nitrate is typically the more useful form of fertilizer. The two fertilizers are also combined to form ammonium nitrate, which is powerful both as a fertilizer and as an

explosive. (Ammonium nitrate was used both in the first World Trade Center bombing, in 1993, and in the even more devastating Oklahoma City bombing two years later.)

Erosion and Soil Conservation

The mismanagement of agricultural lands, and/or the influence of natural forces, can produce devastating results, as illustrated by events during the years 1934 and 1935 in a region including Texas, Oklahoma, Kansas, and eastern Colorado. In just a few months, once-productive farmland turned into worthless fields of stubble and dust, good for virtually nothing. By the time it was over, the region had acquired a bitter nickname: the "dust bowl."

Ironically, in the years leading up to the early 1930s the future dust bowl farmlands had seemed remarkably productive. Farmers happily reaped abundant yields, year after year, not knowing that they were actually preparing the way for soil erosion on a grand scale. Farmers in the 1930s had long known about the principle of crop rotation as a means of giving the soil a rest and restoring its nutrients. But to be successful, crop rotation must include fallow years (i.e., no crops are planted), and must make use of crops that replenish the soil of nutrients.

Cotton and wheat are examples of crops that deplete nutrient content in the soil, and in fact wheat was the crop of choice in the future dust bowl. In some places, farmers alternated between wheat cultivation and livestock grazing on the same plot of land. The hooves of the cattle further damaged the soil, already weakened by raising wheat. The land was ready to become the site of a full-fledged natural disaster, and in the depths of the Great Depression, that disaster came in the form of high winds. These winds scattered vast quantities of soil from the Great Plains of the Midwest to the Atlantic seaboard, and acreage that once had rippled with wheat turned into desert-like wastelands.

The farmlands of the plains states have long since recovered from the dust bowl, and farming practices have changed considerably. Instead of alternating one year of wheat with a year of grazing livestock, farmers in the dust bowl region apply a three-year cycle of wheat, sorghum, and fallow land. They also have planted trees to serve as barriers against wind.

Years after the dust bowl, the American West could have again become the site of another disaster, had not farmers and agricultural officials learned from the mistakes of an earlier generation. During the 1970s, American farms enjoyed such a great surplus that farmers increasingly began to sell their crops to the Soviet Union, and farmers were encouraged to cultivate even marginal croplands to increase profits. This alarmed environmental activists, who called attention to the flow of nutrients from croplands into water resources. As a result of public concerns over these and related issues, Congress in 1977 passed the Soil and Water Resource Conservation Act, mandating measures to conserve or protect soil, water, and other resources on private farmlands and other properties.

Leaching and Its Effect on Soil

Like erosion, leaching moves substances through soil, only in this case it is a downward movement. Leached water can carry all sorts of dissolved substances, ranging from nutrients to contaminants. The introduction of manufactured contaminants to the soil, and hence the water table, is of course a serious threat to the environment. On the other hand, where human waste and other, more natural forms of toxin are concerned, nature itself is able to achieve a certain amount of cleanup on its own.

In a septic tank system, used by people who are not connected to a municipal sewage system, anaerobic bacteria process wastes, removing a great deal of their toxic content in the tank itself. (These bacteria usually are not introduced artificially to the tank; they simply congregate in what is a natural environment for them.) The wastewater leaves the tank and passes through a drain field, in which the water leaches through layers of gravel and other filters that help remove more of its harmful content. In the drain field, the waste is subjected to aerobic decay by other forms of bacteria before it either filters through the drainpipes into the ground or is evaporated.

In addition to purifying water, leaching also passes nutrients to the depths of the A horizon and into the B horizon—something that is not always beneficial. In some ecosystems, leaching removes large amounts of dissolved nitrogen from the soil, and it becomes necessary to fertilize the soil with nitrate. However, soil often has

difficulty binding to nitrate, which tends to leach easily, and this leads to an overabundance of nitrogen in the lower levels of the soil and groundwater. This is a condition known as nitrogen saturation, which can influence the eutrophication of waters (a topic discussed later) and cause the decline and death of trees with roots in an affected area of ground.

How Deserts Are Formed

Let us now consider what one might call an *extreme* ecosystem: a desert. Of the world's deserts, by far the most impressive is the Sahara, which today spreads across some 3.5 million sq. mi. (9.06 million sq km), an area that is larger than the continental United States. Only about 780 acres (316 hectares) of it, a little more than 1 sq. mi. (2.6 sq km), is fertile. The rest is mostly stone and dry earth with scattered shrubs—and here and there the rolling sand dunes typically used to depict the Sahara in movies.

Just 8,000 years ago—the blink of an eye in terms of Earth's timescale—it was a region of flowing rivers and lush valleys. For thousands of years it served as a home to many cultures, some of them quite advanced, to judge from their artwork. Though they left behind an extraordinary record in the form of their rock-art paintings and carvings, which show an understanding of realistic representation that would not be matched until the time of the Greeks, the identity of the early Saharan peoples themselves remains largely a mystery.

EVOLUTION OF THE ANCIENT SAHARAN ECOSYSTEM. The phases in ancient Saharan cultures are identified by the names of the domesticated animals that dominated at given times, and collectively these names tell the story of the Saharan ecosystem's transformation from forest to grassland to desert. First was the Hunter period, from about 6000 to about 4000 B.C., when a Paleolithic, or Old Stone Age, people survived by hunting the many wild animals then available in the region. Next came the Herder period, from about 4000 to 1500 B.C. As their name suggests, these people maintained herds of animals and also practiced basic agriculture.

A high point of ancient Saharan civilization came with the Herder period, which, not surprisingly, also marked the high point of the local ecosystem in terms of its ability to sustain varied life-forms. Yet through a complex set of circumstances that scientists today do not understand fully, desertification—the slow transformation of ordinary lands to desert—had begun to set in. As the Sahara became drier and drier, the herds disappeared.

Eventually, the Egyptians began bringing in domesticated horses to cross the desert: hence the name of the Horse period (*ca.* 1500–*ca.* 600 B.C.), when the Sahara probably resembled the dry grasslands of western Texas or the sub-Saharan savanna in Africa today. By about 600 B.C., however, the climate had become so severe, the water supply so limited, and the ecosystem so depleted of supporting life-forms that not even horses could survive in the forbidding climate. There was only one mammal that could: the hardy, seemingly inexhaustible creature that gave its name to the Camel era, which continues to the present day.

CONTROLLING DESERTIFICATION. What happened to the Sahara? The answer is a complex one, as is the subject of desertification. Desertification does not always result in what people normally think of as a desert; rather, it is a process that contributes toward making a region more dry and arid, and because it is usually gradual, it can be reversed in some cases. Nor is it necessary for a society to undertake large-scale mechanized agricultural projects, such as those of the American dust bowl of the 1930s, to do long-term damage that can result in desertification. The Pueblan culture of what is now the southwestern United States depleted an already dry and vulnerable region after about A.D. 800 by removing its meager stands of mesquite trees.

And though human causes, either in the form of mismanagement or deliberate damage, certainly have contributed to desertification, sometimes nature itself is the driving force. Long-term changes in rainfall or general climate, as well as water erosion and wind erosion such as caused the dust bowl, can turn a region into a permanent desert. An ecosystem may survive short-term drought, but if soil is forced to go too long without proper moisture, it sets in motion a chain reaction in which plant life dwindles and, with it, animal life. Thus, the soil is denied the fresh organic material necessary to its continued sustenance, and a slow, steady process of decline begins.

The Phosphorus Cycle

Having examined what can go wrong (and right) in soil, a key component of the biosphere, we will devote the remainder of this essay to two other aspects of the biosphere mentioned earlier: biogeochemical cycles and the hydrologic cycle. In the context of biogeochemical cycles, we will look at the phosphorus cycle, along with eutrophication—another instance of "what can go wrong."

Because of its high reactivity with oxygen, phosphorus is used in the production of safety matches, smoke bombs, and other incendiary devices. It is also important in various industrial applications and in fertilizers. In fact, ancient humans used phosphorus without knowing it when they fertilized their crops with animal bones. In the early 1800s chemists recognized that the critical component in the bones was the phosphorus, which plants use in photosynthesis—the biological conversion of energy from the Sun into chemical energy. With this discovery came the realization that phosphorus would make an even more effective fertilizer when treated with sulfuric acid, which makes it soluble, or capable of being dissolved, in water. This compound, known as superphosphate, can be produced from phosphate, a type of phosphorus-based mineral.

Microorganisms in the biosphere absorb insoluble phosphorus compounds and, through the action of acids within the microorganisms, turn them into soluble phosphates. These soluble phosphates then are absorbed by algae and other green plants, which are eaten by animals. When they die, the animals, in turn, release the phosphates back into the soil. As with all elements, the total amount of phosphorus on Earth stays constant, but the distribution of it does not. Some of the phosphorus passes from the geosphere into the biosphere, but the vast majority of it winds up in the ocean. It may find its way into sediments in shallow waters, in which case it continues to circulate, or it may be taken to the deep parts of the seas, in which case it is likely to be deposited for the long term.

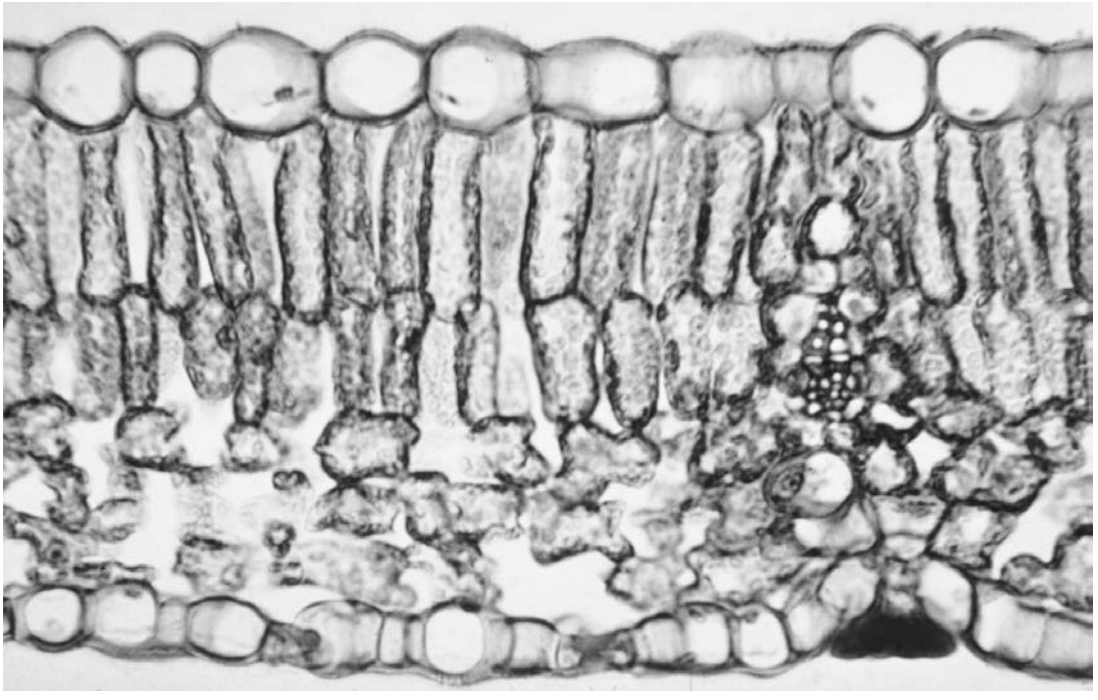
Because fish absorb particles of phosphorus, some of it returns to dry land through the catching and consumption of seafood. Also, guano or dung from birds that live in an ocean environment (e.g., seagulls) returns portions of phosphorus to the terrestrial environment. Nevertheless, scientists believe that phosphorus is steadily being transferred to the ocean, from whence it is not likely to return. It is for this reason that phosphorus-based fertilizers are important, because they feed the soil with nutrients that would otherwise be steadily lost. However, phosphorus still ends up making its way through the waters, and this creates a serious problem in the form of eutrophication.

EUTROPHICATION. Eutrophication (from a Greek term meaning "well nourished") is a state of heightened biological productivity in a body of water. One of the leading causes of eutrophication is a high rate of nutrient input, in the form of phosphate or nitrate, a nitrogen-oxygen compound. As a result of soil erosion, fertilizers make their way into bodies of water, as does detergent runoff in wastewater. Excessive phosphates and nitrates stimulate growth in algae and other green plants, and when these plants die, they drift to the bottom of the lake or other body of water. There, decomposers consume the remains of the plants, and in the process of doing so, they also use oxygen that otherwise would be available to fish, mollusks, and other forms of life. As a result, those species die off, to be replaced by others that are more tolerant of lowered oxygen levels—for example, worms. Needless to say, the outcome of eutrophication is devastating to the lake's ecosystem.

Lake Erie—one of the Great Lakes on the border of the United States and Canada—became an extreme example of eutrophication in the 1960s. As a result of high phosphate concentrations, Erie's waters were choked with plant and algae growth. Fish were unable to live in the water, the beaches reeked with the smell of decaying algae, and Erie became widely known as a "dead" body of water. This situation led to the passage of new environmental standards and pollution controls by both the United States and Canada, whose governments acted to reduce the phosphate content in fertilizers and detergents drastically. Within a few decades, thanks to the new measures, the lake once again teemed with life. Thus, Lake Erie became an environmental success story.

Evapotranspiration

Many of the phenomena and processes we have described tie together the biosphere with other "spheres" of Earth. Such is the case with evapo-



Cross section of a lilac leaf. A key element in circulating life-sustaining materials among the various earth systems is transpiration, the evaporation of moisture from plants. Plants lose their water through membranes of a tissue known as spongy mesophyll (shown here), found in the tiny cavities that lie beneath the microscopic leaf pores called stomata. *(© Lester V. Bergman/Corbis. Reproduced by permission.)*

transpiration, the sum total of evaporation and transpiration. The second of these terms is less well-known than the first, but the words in fact refer to the same process. The only difference is that evaporation involves the upward movement of water from nonliving sources, while transpiration is the evaporation of moisture from living sources.

Transpiration is at least as important as evaporation when it comes to putting moisture into the atmosphere. It actually puts more water into the air than evaporation does: any large area of vegetation tends to transpire much larger quantities of moisture than an equivalent nonfoliated region, such as the surface of a lake or moist soil. Though animals can play a part in transpiration, plant transpiration has much greater environmental significance.

Water in plants is lost through moist membranes of a tissue known as spongy mesophyll, found in the tiny cavities that lie beneath the microscopic leaf pores called stomata. Stomata remain open most of the time, but when they need to be closed, guard cells around their borders push them shut. Because plants depend on stomata to "breathe" by pulling in carbon dioxide, they keep them open—just as a human's pores must remain open. Otherwise, the person would not take in enough oxygen, and would perish.

The fact that the stomata are exposed in order to receive carbon dioxide for the plant's photosynthesis also means that the stomata are open to allow the loss of moisture to the atmosphere. It can be said, then, that transpiration in plants—vital as it is to the functioning of our atmosphere—is actually an unavoidable consequence of photosynthesis, an unrelated process. (See Carbohydrates for more about photosynthesis.)

ANIMAL TRANSPIRATION. Transpiration in animals (including humans) takes place for much the same reason as it does with plants: as a by-product of breathing. Animals have to keep their moist respiratory surfaces, such as the lungs, open to the atmosphere. We may not think of our own breathing as transferring moisture to the air, but the presence of moisture in our lungs can be proved simply by breathing on a piece of glass and observing the misty cloud that lingers there.

Transpiration can cause animals to become dehydrated, but it also can be important in cooling down their bodies. When human bodies

KEY TERMS

A HORIZON: Topsoil, the uppermost of the three major soil horizons. This layer and the humus that lies above it house all the organic content in soil.

AEROBIC: Oxygen-breathing.

ANAEROBIC: Non-oxygen-breathing.

ATMOSPHERE: Earth's atmosphere is a blanket of gases that includes nitrogen (78%), oxygen (21%), argon (0.93%), and a combination of water vapor, carbon dioxide, ozone, and noble gases such as neon (0.07%). Most of these gases are contained in the troposphere, the lowest layer, which extends to about 10 mi. (16 km) above the planet's surface.

B HORIZON: Subsoil, beneath topsoil and above the C horizon. Though the B horizon contains no organic material, its presence is critical if the soil is to be suitable for sustaining a varied ecosystem.

BIOGEOCHEMICAL CYCLES: The changes that particular elements undergo as they pass back and forth through the various earth systems (e.g., the biosphere) and particularly between living and nonliving matter. The elements involved in biogeochemical cycles are hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur.

BIOSPHERE: A combination of all living things on Earth—plants, animals, birds, marine life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

C HORIZON: The bottommost of the soil horizons, between subsoil and bedrock. The C horizon is made of regolith, or weathered rock.

CANOPY: The upper portion or layer of the trees in a forest. A forest with a closed canopy is one so dense with vegetation that the sky is not visible from the ground.

CLIMATE: The pattern of weather conditions in a particular region over an extended period. Compare with *weather.*

CLOSED SYSTEM: A system that permits the exchange of energy with its external environment but does not allow matter to pass between the environment and the system. Compare with *isolated system* on the one hand and *open system* on the other.

COMPOUND: A substance made up of atoms, chemically bonded to one another, of more than one chemical element.

DECOMPOSERS: Organisms that obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. The principal forms of decomposer are bacteria and fungi.

DECOMPOSITION REACTION: A chemical reaction in which a compound is broken down into simpler compounds, or into its constituent elements. In the biosphere, this often is achieved through the help of detritivores and decomposers.

DETRITIVORES: Organisms that feed on waste matter, breaking organic material down into inorganic substances that then can become available to the biosphere in the form of nutrients for plants. Their function is similar to that of decomposers; however, unlike decomposers—which tend

KEY TERMS CONTINUED

to be bacteria or fungi—detritivores are relatively complex organisms, such as earthworms or maggots.

ECOLOGY: The study of the relationships between organisms and their environments.

ECOSYSTEM: A community of interdependent organisms along with the inorganic components of their environment.

ELEMENT: A substance made up of only one kind of atom. Unlike compounds, elements cannot be broken down chemically into other substances.

EUTROPHICATION: A state of heightened biological productivity in a body of water, which is typically detrimental to the ecosystem in which it takes place. Eutrophication can be caused by an excess of nitrogen or phosphorus, in the form of nitrates and phosphates, respectively.

EVAPORATION: The process whereby liquid water is converted into a gaseous state and transported to the atmosphere. When discussing the atmosphere and precipitation, usually evaporation is distinguished from transpiration. In this context, evaporation refers solely to the transfer of water from nonliving sources, such as the soil or the surface of a lake.

EVAPOTRANSPIRATION: The loss of water to the atmosphere via the combined (and related) processes of evaporation and transpiration.

FOOD WEB: A term describing the interaction of plants, herbivores, carnivores, omnivores, decomposers, and detritivores in an ecosystem. Each of these organisms consumes nutrients and passes it along to other organisms. Earth scientists typically prefer this name to *food chain,* an everyday term for a similar phenomenon. A food chain is a series of singular organisms in which each plant or animal depends on the organism that precedes it. Food chains rarely exist in nature.

GEOSPHERE: The upper part of Earth's continental crust, or that portion of the solid earth on which human beings live and which provides them with most of their food and natural resources.

HUMUS: Unincorporated, often partially decomposed plant residue that lies at the top of soil and eventually will decay fully to become part of it.

HYDROCARBON: Any organic chemical compound whose molecules are made up of nothing but carbon and hydrogen atoms.

HYDROLOGIC CYCLE: The continuous circulation of water throughout Earth and between various earth systems.

HYDROSPHERE: The entirety of Earth's water, excluding water vapor in the atmosphere but including all oceans, lakes, streams, groundwater, snow, and ice.

ISOLATED SYSTEM: A system that is separated so fully from the rest of the universe that it exchanges neither matter nor energy with its environment. This is an imaginary construct, since full isolation is impossible.

LEACHING: The removal of soil materials that are in solution, or dissolved in water.

MINERAL: A naturally occurring, typically inorganic substance with a specific

KEY TERMS CONTINUED

chemical composition and a crystalline structure. A crystalline structure is one in which the constituent parts have a simple and definite geometric arrangement that is repeated in all directions.

OPEN SYSTEM: A system that allows complete, or near complete, exchange of matter and energy with its environment.

ORGANIC: At one time, chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals) and oxides, such as carbon dioxide.

PATHOGEN: A disease-carrying parasite, usually a microorganism.

PHOTOSYNTHESIS: The biological conversion of light energy (that is, electromagnetic energy) from the Sun to chemical energy in plants.

SOLUBLE: Capable of being dissolved.

SYSTEM: Any set of interactions that can be set apart mentally from the rest of the universe for the purposes of study, observation, and measurement.

WEATHER: The condition of the atmosphere at a given time and place. Compare with *climate.*

become overheated, they produce perspiration, which cools the surface of the skin somewhat. If the air around us is too humid, however, then it already is largely saturated with water, and the perspiration has no place to evaporate. Therefore, instead of continuing to cool our bodies, the perspiration simply forms a sticky film on the skin. But assuming the air is capable of absorbing more moisture, the sweat will evaporate, cooling our bodies considerably.

EFFECTS OF HEAT AND COLD. When summer is at its height, air temperatures are warm and the trees are fully foliated (i.e., covered in leaves), and a high rate of transpiration occurs. So much water is pumped into the atmosphere through foliage that the rate of evapotranspiration typically exceeds the input of water to the local environment through rainfall. The result is that soil becomes dry, some streams cease to flow, and by late summer in extremely warm temperate areas, such as the southern United States, there is a great threat of drought and related problems, such as forest fires.

As trees drop their leaves in the autumn, transpiration rates decrease greatly. This makes it possible for the parched soil to become recharged by rainfall and for streams to flow again. Such is the case in a temperate region, which, by definition, is one that has the four seasons to which most people in the United States (outside Hawaii, Alaska, and extreme southern Florida and Texas) are accustomed. In a tropical region, by contrast, there is a "dry season," in which transpiration takes place, and a "rainy season," in which moisture from the atmosphere inundates the solid earth. This rainy season may be so intense that it produces floods.

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ECOSYSTEMS AND ECOLOGY

CONCEPT

Composed of living organisms and the remains of living things as well as the nonliving materials in their surroundings, an ecosystem is a complete community. Its components include plants, animals, and microorganisms, both living and dead; soil, rocks, and minerals; water sources above and below ground; and the local atmosphere. An ecosystem can consist of an entire rain forest, geographically larger than many nations, or it can be as small as the body of an animal, which is likely to comprise far more microorganisms than there are people on Earth. Among the most significant areas of interest in the realm of ecosystems is ecology, or the study of the relationships between organisms and their environments. Forests, a broad category of ecosystem, provide a living laboratory in which to investigate the ways in which organisms interact with their environments. They also aptly illustrate the stresses placed on ecosystems by human activities.

HOW IT WORKS

The Biosphere and Food Webs

In the sciences, a system is any set of interactions that can be set apart mentally from the rest of the universe for the purposes of study, observation, and measurement. Modern earth scientists regard the planet as a massive ecosystem, the stage on which four extraordinarily complex earth systems interact. These systems are the atmosphere, the hydrosphere (all the planet's waters, except for moisture in the atmosphere), the geosphere (the soil and the extreme upper portion of the continental crust), and the biosphere.

The biosphere consists of all living things—microorganisms, plants, insects, birds, marine life, and all other forms of animals—as well as formerly living things that have not yet decomposed. (Decomposed remains of organic materials become part of the geosphere, specifically the soil.) Organisms in the biosphere, whether living or formerly living, are united by the interrelation of energy transfer that takes place through the food web.

A food web is similar to the more well known expression food chain. In scientific terms, however, a food chain is defined as a series of singular organisms in which each plant or animal depends on the organism that precedes or follows it. This rarely exists in nature; instead, the feeding relationships between organisms in the real world are much more complex and are best described as a web rather than a chain. (For more on the biosphere and earth systems, see The Biosphere.)

Energy Flow and Nutrients

Energy is the ability of objects or systems to accomplish work. (The latter is defined as the exertion of force over a given distance: for example, a plant growing from the ground, an insect or bird flying, or a human or pack animal moving an object.) Food webs are built around energy transfer, or the flow of energy between organisms, which begins with plant life. Hence the importance of plants to ecosystems, as we illustrate later in discussing various types of forest, which are defined by their dominant varieties of tree.

Plants absorb energy in two ways. From the Sun they receive electromagnetic energy in the form of visible light and invisible infrared waves, which they convert to chemical energy by means

of photosynthesis. In addition, plants take in nutrients from the soil, which contains energy in the forms of various chemical compounds. These compounds may be organic, which typically means that they came from living things, though, strictly speaking, organic refers to characteristic carbon-based chemical structures. Plants also receive inorganic compounds from minerals in the soil. (See Paleontology for an explanation of the scientific distinction between organic and inorganic.)

Contained in these minerals are six chemical elements essential to the sustenance of life on planet Earth: hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur. These are the elements involved in biogeochemical cycles, through which they are circulated continually between the living and nonliving worlds—that is, between organisms on the one hand and the inorganic realms of rocks, minerals, water, and air on the other. (See The Biosphere for more about biogeochemical cycles.)

FROM PLANTS TO MEAT EATERS. As plants take up nutrients from the soil, they convert them into other forms. Eventually, the plants themselves become food either for herbivores (plant-eating organisms) or for omnivores (organisms that eat both plants and other animals), thus passing along these usable, energy-containing chemical compounds to other participants in the food web. It is likely that an herbivore will be eaten in turn either by an omnivore (for example, humans as well as a number of bird species and many others) or by a carnivore, an organism that eats only meat.

Carnivores and omnivores are not usually prey for other carnivores or omnivores, but this does happen in the case of what are known as tertiary consumers (see Food Webs). There is also the matter of cannibalism, discussed in Biological Communities. For the most part, however, the only creatures that eat carnivores and omnivores do so after these organisms have died or been killed.

DETRITIVORES AND DECOMPOSERS. An animal that obtains its energy in this way, from consuming the carcasses of carnivores and omnivores (as well as herbivores and perhaps even plants), is known as a detritivore. Large and notable examples include vultures and hyenas, though most detritivores—earthworms or maggots, for instance—are much smaller. Nonetheless, detritivores are relatively large, complex organisms compared with another variety of species that occupies a level or position in the food web that comes "after" carnivores and omnivores: decomposers, including bacteria and fungi.

This illustrates the reason why ecological sciences treat the expression food chain with disfavor. There is no such thing as "the top of the food chain," rather, there are simply stages, like a circular assembly line, with detritivores occupying a position between meat-eating animals and plants. Earthworms, in particular, help convert animal bodies into soil nutrients useful to the growth of plant life, yet even these and other detritivores must themselves eventually be converted to soil as well.

This "final" stage of conversion—that is, the last stop after the animal portion of the food web and before the cycle comes back around to ordinary plants—is occupied by decomposers, such as bacteria and fungi. These decomposers obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. Like detritivores, they aid in decomposition, a chemical reaction in which a compound is broken down into simpler compounds, or into its constituent elements.

Often an element such as nitrogen appears in forms that are not readily usable to organisms, and therefore such elements (which may appear individually or in compounds) need to be processed chemically through the body of a decomposer or detritivore. This process brings about a chemical reaction in which the substance (whether an element or compound) is transformed into a more usable version. By processing these chemical compounds, decomposers and detritivores provide nutrients necessary to plant growth.

REAL-LIFE APPLICATIONS

Forests and Ecology

One easily understandable example of ecosystems and ecology in action is the forest. Virtually everyone has visited a forest at one time or another, and those who are enthusiasts for the great outdoors may spend a great deal of time in one. In the past, of course, people interacted with



A variety of angiosperm, mangrove trees are found in low-lying, muddy regions near saltwater, where the climate is humid. A mangrove forest is poor in species: only organisms that can tolerate flooding and high salt levels are capable of surviving. *(© Wolfgang Kaehler/Corbis. Reproduced by permission.)*

forests not so much out of choice, and certainly not with recreation as the foremost aim in mind, but simply because they depended on the forest for survival. Not only did the forest provide hunters and food-gatherers with an abundance of wildlife and fruit, but trees provided material for building dwellings. It is no wonder, then, that many early human settlements tended to be in, or at the edges of, forests.

A forest is simply an ecosystem dominated by trees. There are many varieties of forest, however, because so many factors go into determining the character of a forest ecosystem. The fact that the forest *is* an ecosystem means that its qualities are defined by far more than just the varieties of trees, which are simply the most visible among many biological forms in the forest. Numerous abiotic, or nonbiological, factors also affect the characteristics of a forest as well. For instance, there is weather, defined as the condition of the atmosphere at a given time and place, and climate, the overall patterns of weather for extended periods.

These play a clear role, for instance, in defining the tropical rain forest, a place where constant rainfall ensures that there are always plenty of plants in flower. Because the trees and other species of vegetation do not all shed at the same time, the rain forest canopy—the upper layer of trees in the forest—remains rich in foliage year-round. Hence, the tropical rain forest is an example of an evergreen forest. Climate can determine the type of life forms capable of surviving in the forest ecosystem. This can be illustrated by referring to a forest almost perfectly opposite in character to a rain forest: the taiga, or boreal forest, that spans much of northern Eurasia.

The taiga is a deciduous forest, meaning that its trees shed their leaves seasonally; indeed, because of the very cold climate in taiga regions, where the temperature during winter is usually well below the freezing point, trees spend a great portion of the year bare. Rainfall is much, much lower than in a rain forest, of course: only about 10-20 in. (250–500 mm) per year, as compared with more than 70 in. (1,800 mm) for a typical rain forest. The dry, inhospitable climate of the taiga makes it a forbidding place for reptiles and amphibians, though the taiga is home to many endothermic (warm-blooded) creatures such as mammals or birds.

LATITUDE, ALTITUDE, AND FORESTS. Elevation or relief—that is, height above sea level—also determines the char-

acter of a forest, as do latitude (distance north or south of the equator) and topography, or the overall physical configuration of Earth's surface in a given area. Rain forests can exist anywhere, but by definition a *tropical* rain forest, such as those along the Amazon River in South America or the Congo River in Africa, must lie between the Tropic of Cancer in the north and the Tropic of Capricorn in the south.

Naturally, in the tropical rain forest, temperatures are high—typically, about 86°F (30°C) during the day, cooling down to about 68°F (20°C) at night. By contrast, there are much cooler rain forests in the temperate zones. An example is the Cherokee National Forest on the border between North Carolina and Tennessee, which, though located in the southeastern United States, is chilly even in the summer months.

Just as latitude affects a forest, so does altitude. Rain forests at relatively high elevations, such as the highlands of New Guinea, are known as montane forests. These forests, though they may be located at the same latitude as tropical rain forests—most montane forests are in eastern Brazil, southeastern Africa, northern Australia, and parts of southeast Asia—are much cooler. Lush by comparison to most non-rain forests, their vegetation is nonetheless much less dense than in a typical tropical rain forest.

In addition to its role in defining the overall character of the forest, differences in relative altitude or elevation resulting from the great height of trees in the rain forest also influence the formation of differing biological communities. For example, monkeys, flying squirrels, and other animals capable of swinging, gliding, or otherwise moving from tree to tree inhabit the canopy, which is rich in well-watered leaves and other food sources. These top-dwellers seldom even need to come down to the ground for anything. The rain forest floor, by contrast, is mostly bare, since the trees above shade it. On this level live creatures such as chimpanzees and gorillas, who feed off of low-lying plant forms. Other biological communities exist above or below the forest floor. (For more on these subjects, including the various types of forests, see Biomes. See The Biosphere for a discussion of soil quality in the rain forest.)

HUMANS AND FORESTS. Earlier we noted the fact that humans' early history kept them, like other primates, close to the forest. In modern times, a growing awareness of ecology, and of the distance that technology has placed between modern society and the forests, led to the movement for the establishment of national parks in general, and of national forests in particular.

The first of these preserves—places where commercial development is forbidden and commercial activity is limited—was Yellowstone National Park in Wyoming, established by the administration of President Ulysses S. Grant in 1872. Though Yellowstone contains enormous areas of forest land, the first national forest reserve (as national forests were called at the time) was Sequoia National Park, established in 1891. Home to some of the largest, most awe-inspiring trees in the world, Sequoia is part of a group of national forests and parks to the northeast of Bakersfield, California.

The United States Forest Service was actually founded earlier (1905) than the National Park Service (1916), a fact that illustrates the importance of pristine forests to maintaining a proper balance between humans and their environment. Since the establishment of the forest service under the aegis of the U.S. Department of Agriculture, the lands controlled by the forest service have grown to encompass about 191 million acres (77.3 million hectares), an area larger than Texas. During the same period, the U.S. example of national parks and forests has inspired nations around the world to create their own preserves.

Coupled with the rise of national parks and forests at the turn of the nineteenth century was a growing interest in conservation and management of environmental resources. This interest manifested across a broad spectrum, from environmentalists who urged that the forests be left in their original state to industrial foresters who view the forest as a resource that can be utilized. Both sides have their merits, and both have their complaints about the other. The close historical ties between conservationism and the science of forestry (the management of forest ecosystems for purposes such as harvesting timber), both of which had their origins during the nineteenth century, suggest that there is no inherent reason that the two sides should be in conflict. If anything, responsible forestry goes hand-in-hand with an attitude of conserving as many resources as is feasible.



By evolving bright colors, scents, and nectar, the flowers of angiosperms attract animals, which travel from one flower to another, moving pollen as they go. Whereas insects and animals pose a threat to gymnosperms, angiosperms put bees, butterflies, hummingbirds, and other flower-seeking creatures to work assisting their reproductive process. *(© Gallo Images/Corbis. Reproduced by permission.)*

Comparing Angiosperms and Gymnosperms

Several times we have referred to angiosperms, a name that encompasses not just certain types of tree but also all plants that produce flowers during sexual reproduction. The name, which comes from Latin roots meaning "vessel seed," is a reference to the fact that the plant keeps its seeds in a vessel whose name, the ovary, emphasizes the sexual quality of the reproductive process it undergoes.

Angiosperms are a beautiful example of how a particular group of organisms can adapt to specific ecosystems and do so in a highly efficient manner, such that the evolutionary future heralds only greater dominance for these species. This is all the more interesting in light of the contrast between the success of the angiosperm and the rather less impressive results achieved by another broad category of sexually reproducing plant, one that formerly dominated Earth's forest: the gymnosperm.

Flowering plants evolved only about 130 million years ago, by which time gymnosperms (of which modern pines are an example) had long since evolved and proliferated. Yet in a relatively short period of time, angiosperms have become the dominant plants in the world today. About 80% of all living plant species are flowering plants, and based on the record of angiosperms and gymnosperms heretofore, it is likely that the world of 100 million years from now will be one in which the forests are typified by angiosperms. Gymnosperms, meanwhile, may well become a dying, if not a dead, breed.

Pollination by gymnosperms. Gymnosperms reproduce sexually as well, but they do so by a much less efficient method than that of the angiosperm. Whereas the angiosperm keeps its seeds safely tucked away inside the ovary and coexists with its ecosystem most favorably by putting the insect and animal life to work, gymnosperm reproduction is an altogether less effective—and, indeed, less pleasant—process.

For starters, gymnosperms produce their seeds on the surface of leaflike structures, and this makes the seeds vulnerable to physical damage and drying as the wind whips the trees' branches back and forth. Furthermore, insects and other animals view gymnosperm seeds as a source of nutrition, as indeed they are. And in contrast to the angiosperm, which attracts bees and other creatures to it, gymnosperms package the male reproductive component in tiny pollen grains, which it releases into the wind.

Eventually, the grains make their way toward the female component of another individual within the same species, but the fact that they do is an example of the wonder inherent in life itself and not of the efficiency of gymnosperm reproduction. Gymnosperms shower their ecosystems with pollen, a fact familiar to anyone who lives in a place with a high gymnosperm population—and hence a high pollen count in the spring. In gymnosperm-heavy environments, yellowish dust forms on everything, and where humans interact with the natural world, this can create a great deal of discomfort in the form of hay fever and allergies. Meanwhile, cars, windowsills, mailboxes, and virtually every other available surface takes on a yellow film that usually is not relieved until a good rain falls or, more likely, pollination ends for the year.

Though pollen is unpleasant to humans, it should be noted that like all natural mechanisms, it benefits the overall ecosystem. Packed with energy, pollen grains contain large quantities of nitrogen, making them a major boost to the nutrient content in the soil. But it costs the gymnosperm a great deal, in terms of chemical and biological energy and material, to produce pollen grains, and the benefits are uncertain.

POLLINATION BY ANGIOSPERMS. If the gymnosperm and angiosperm varieties of pollination were compared to marketing campaigns, gymnosperm reproduction would involve the client (i.e., the gymnosperms themselves) investing maximum capital for minimal returns. In a very real sense, gymnosperm pollination is like the marketing of a company that bombards a neighborhood with leaflets, such that advertising rapidly becomes another form of trash simply to be swept up and thrown away.

By contrast, the "marketing" of angiosperms is like that of a company that uses carefully targeted, researched advertising, utilizing as many free means as possible for getting out word about itself. Just as a smart marketer sets in place the conditions to get consumers talking about a product—thus using advertising that is both free and extremely effective—the angiosperm enlists the aid of mobile organisms in its environment.

In addition, the angiosperm puts a great deal of its energy into producing reproductive structures, an effort that pays off bountifully. By evolving bright colors, scents, and nectar, the flowers of angiosperms attract animals, which travel from one flower to another, unintentionally moving pollen as they go. Thus, whereas insects and animals pose a threat to gymnosperms, angiosperms actually put bees, butterflies, hummingbirds, and other flower-seeking creatures to work assisting their reproductive process.

Because of this remarkably efficient system, animal-pollinated species of flowering plants do not need to produce as much pollen as gymnosperms. They can put their resources into other important functions instead, such as growth and greater seed production. In this way, the angiosperm solves its own problem of reproduction—and, as a side benefit, adds enormously to the world's beauty.

DEFORESTATION

Returning to the subject of forests in general, if a forest experiences significant disturbance, it may undergo deforestation. Despite the finality in the sound of the word, deforestation does not necessarily imply complete destruction of the forest. In fact, *deforestation* can describe any interruption in the ordinary progression of a forest's life, including clear-cut harvesting—even if the forest fully recovers.

Deforestation can occur naturally, as a result of changes in the soil and climate, but the most significant cases of deforestation over the past few thousand years have been the consequence of human activities. Usually deforestation is driven by the need to clear land to harvest trees for fuel or, in some cases, to obtain building materials in the form of lumber. Though deforestation has been a problem the world over, since the 1970s it has become an issue primarily in developing countries.

In developed nations such as the United States, environmental activism has raised public awareness concerning deforestation and led to curtailment of large-scale cutting in forests that are deemed important environmental habitats. By contrast, developing nations, such as Brazil, are cutting down their forests at an alarming rate. Generally, economics is the dominant factor, with the need for new agricultural land or the desire to obtain wood and other materials typically driving the deforestation process.

CONSEQUENCES OF DEFORESTATION. The deforestation of valuable reserves such as the Amazon rain forest is an environmental disaster in the making. As discussed in the essay The Biosphere, the soil in rain forests as a rule is "old," and leached of nutrients. Without the constant reintroduction of organic material from the plants and animals of the rain forests, it would be too poor to grow anything. Therefore, when nations cut down their own rain forest lands, they are in effect killing the golden goose to get at the egg: once the rain forest is gone, the land itself is worthless.

Deforestation has several other extremely serious consequences. From a biological standpoint, it greatly reduces biodiversity, or the range of species in the biota. In the case of tropical rain forests as well as old-growth forests (see Biological Communities), certain species cannot survive once the environmental structure has been rup-



A lone tree trunk stands in an area of deforested grassland in Maranhão, Brazil. The deforestation of valuable reserves such as the Amazon rain forest is an environmental disaster in the making, depleting and starving the soil, reducing biodiversity, and bringing about dangerous changes in atmospheric carbon content. *(© Barnabas Bosshart/Corbis. Reproduced by permission.)*

tured. From an environmental perspective, it leads to dangerous changes in the carbon content of the atmosphere, discussed later in this essay. In the case of old-growth forests or rain forests, deforestation removes an irreplaceable environmental asset that contributes to the planet's biodiversity—and to its oxygen supply.

Even from a human standpoint, deforestation takes an enormous toll. Economically, it depletes valuable forest resources. Furthermore, deforestation in many developing countries often is accompanied by the displacement of indigenous peoples, while still other political and social horrors may lurk in the shadows. For example, Brazil's forests are home to charcoal factories that amount to virtual slave-labor camps. Aboriginal peoples (i.e., "Indians") are lured from cities with promises of high income and benefits, only to arrive and find that the situation is quite different from what was advertised. Having paid the potential employer for transportation to the work site, however, they are unable to afford a return ticket and must labor to repay the cost.

The Greenhouse Effect

The most potentially serious aspect of cutting down forests may well be the greenhouse effect, which some scientists and activists believe is causing an overall warming of the planet. Today, thanks to the popularity of environmental causes among entertainment figures and on college campuses, terms such as "the greenhouse effect" and "global warming" are commonplace. However, these phrases are used so frequently, and sometimes so confusingly or misleadingly, that it is worthwhile to address their meaning briefly; then, we can conclude our discussion by looking at what impact the steady reduction in forest lands has had on the increasing release of greenhouse gases.

The greenhouse effect itself is not a consequence of any action on the part of human beings; rather, it is a part of life on Earth. In fact, without it, there could *be* no life on Earth. Though the planet receives an incredible amount of energy from the Sun, much of it is lost by being absorbed or reflected in the atmosphere or on the surface. So-called greenhouses gases such as carbon dioxide, however, help to trap this energy, keeping much more of the Sun's warmth

KEY TERMS

ANGIOSPERM: A type of plant that produces flowers during sexual reproduction.

ATMOSPHERE: Earth's atmosphere is a blanket of gases that includes nitrogen (78%), oxygen (21%), argon (0.93%), and a combination of water vapor, carbon dioxide, ozone, and noble gases such as neon (0.07%). Most of these gases are contained in the troposphere, the lowest layer, which extends to about 10 mi. (16 km) above the planet's surface.

BIODIVERSITY: The degree of variety among the species represented in a particular ecosystem.

BIOLOGICAL COMMUNITY: The living components of an ecosystem.

CANOPY: The upper portion or layer of the trees in a forest. A forest with a closed canopy is one so dense with vegetation that the sky is not visible from the ground.

CARNIVORE: A meat-eating organism, or an organism that eats *only* meat (as distinguished from an omnivore).

COMPOUND: A substance made up of atoms, chemically bonded to one another, of more than one chemical element.

CONIFER: A type of tree that produces cones bearing seeds.

DECIDUOUS: A term for a tree or other form of vegetation that sheds its leaves seasonally.

DECOMPOSERS: Organisms that obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. The principal forms of decomposer are bacteria and fungi.

DECOMPOSITION REACTION: A chemical reaction in which a compound is broken down into simpler compounds or into its constituent elements. In the earth system, this often is achieved through the help of detritivores and decomposers.

DEFORESTATION: A term for any interruption in the ordinary progression of a forest's life.

DETRITIVORES: Organisms that feed on waste matter, breaking down organic material into inorganic substances that then can become available to the biosphere in the form of nutrients for plants. Their function is similar to that of decomposers; however, unlike decomposers—which tend to be bacteria or fungi—detritivores are relatively complex organisms, such as earthworms or maggots.

ECOLOGY: The study of the relationships between organisms and their environments.

ECOSYSTEM: A community of interdependent organisms along with the inorganic components of their environment.

ELEMENT: A substance made up of only one kind of atom. Unlike compounds, elements cannot be broken chemically into other substances.

ENERGY: The ability of an object (or in some cases a nonobject, such as a magnetic force field) to accomplish work.

ENERGY BUDGET: The total amount of energy available to a system or, more specifically, the difference between the

KEY TERMS CONTINUED

energy flowing into the system and the energy lost by it.

ENERGY TRANSFER: The flow of energy between organisms in a food web.

FOOD WEB: A term describing the interaction of plants, herbivores, carnivores, omnivores, decomposers, and detritivores in an ecosystem. Each of them consumes nutrients and passes it along to other organisms. Earth scientists typically prefer this name to *food chain,* an everyday term for a similar phenomenon. A food chain is a series of singular organisms in which each plant or animal depends on the organism that precedes it. Food chains rarely exist in nature.

FOREST: In general terms, a forest is simply any ecosystem dominated by tree-size woody plants. A number of other characteristics and parameters (for example, weather, altitude, and dominant species) further define types of forests, such as tropical rain forests.

GREENHOUSE EFFECT: Warming of the lower atmosphere and surface of Earth. This occurs because of the absorption of long-wavelength radiation from the planet's surface by certain radiatively active gases, such as carbon dioxide and water vapor, in the atmosphere. These gases are heated and ultimately re-radiate energy at an even longer wavelength to space. (Wavelength and energy levels are related inversely; hence, the longer the wavelength, the less the energy.)

GYMNOSPERM: A type of plant that reproduces sexually through the use of seeds that are exposed, not hidden in an ovary as with an angiosperm.

HERBIVORE: A plant-eating organism.

OMNIVORE: An organism that eats both plants and other animals.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals) and oxides, such as carbon dioxide.

PHOTOSYNTHESIS: The biological conversion of light energy (that is, electromagnetic energy) from the Sun to chemical energy in plants.

SYSTEM: Any set of interactions that can be set apart mentally from the rest of the universe for the purposes of study, observation, and measurement.

within Earth's atmosphere, much as a greenhouse helps trap heat. Without the greenhouse effect, Earth would be so cold that the oceans would freeze.

Obviously, then, the greenhouse effect is a good thing—but only if greenhouse gases are kept at certain levels. Earth, after all, is not the only planet in the solar system that experiences a greenhouse effect; there is also Venus, a hellish place where surface temperatures are as high as 932°F (500°C). To many environmentalists, there is a grave danger that Earth could be slowly going the way of Venus, building up greenhouse gases such that the temperature is slowly increasing. This is the phenomenon of global warming, which threatens to melt the polar ice caps and submerge much of Earth's land surface. At least, that is the opinion of environmentalists and others who subscribe to the idea that Earth is steadily warming as a result of human pollution and industrial activity.

There is a considerable body of scientific knowledge that challenges the environmentalist position on global warming and the greenhouse effect, but it is not our purpose here to judge the various positions. Rather, our concern is the link between forests and the increase of greenhouses gases in the atmosphere. Old-growth or mature forests of the type discussed in Succession and Climax contain vast amounts of carbon—the basis for all living things—and when these forests are cut down, that carbon has to go somewhere. Specifically, carbon, in the form of carbon dioxide, will be released into the atmosphere, increasing the amount of greenhouse gases there.

This release may occur quickly, as when wood is burned, or more slowly, if the timber from the forest is used over long periods of time—for instance, in the building of houses or other structures. Statistics suggest an alarming change in the amount of carbon in the forests as compared with that in the atmosphere: since about 1850, the amount of carbon stored in forests had dropped by about one-third, while the amount of carbon dioxide in the atmosphere has increased by a comparable factor. Thus, the effort to keep greenhouse gases at viable levels is inextricably tied to the movement to preserve forest ecosystems.

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BIOMES

CONCEPT

On a political map of the world, Earth is divided into countries, of which there are almost 200. But nature, of course, knows no national boundaries, and therefore the natural divisions of the planet are quite different from those agreed upon by humans. While continents are a useful concept to geographers and earth scientists, in the worlds of biology, ecology, and biogeography, the concept of a biome makes much more sense. There are more than a dozen basic terrestrial and aquatic biomes or ecosystems, including boreal coniferous forests, deserts, tundra, and underwater environments. Each is a distinct "world" unto itself, with characteristic forms of plant life as well as animal species that congregate around the plants for food or shelter or both. Combined with these features of the biological community are aspects of the inorganic realm that likewise define a biome, for instance, climate and the availability of water.

HOW IT WORKS

Ecosystems, Biomes, and Biological Communities

An ecosystem is a community of interdependent organisms along with the inorganic components of their environment, including water, soil, and air. Earth is the largest ecosystem, divided into biomes, large areas with similar climate and vegetation. A biome is a large ecosystem, extending over a wide geographic region, characterized by certain dominant life-forms—most notably, trees or the lack thereof. There are two basic varieties of biome: terrestrial, or land-based (of which there are six), and aquatic. The second of these types is divided further into marine and freshwater biomes.

Within a biome or ecosystem, the sum of all living organisms is referred to as the *biological community.* Sometimes the term *biota,* which refers to all flora and fauna (plants and animals) in a region, is used instead. Thus, biological community is a larger concept, since it includes microorganisms, which are vital to the functioning of the food web. The food web, which may be thought of as an interconnected network of food chains, is the means by which energy is transferred through a biological community. Without microorganisms known as decomposers, a key link in the food web would be missing. (See Food Webs for more on this subject.)

Succession and climax. Over the course of time, ecosystems experience a process known as *succession,* the progressive replacement of one biological community by another. This is rather like the series of changes one might witness if one were to record the activity on a major city block over the space of a few decades, as stores come in and shut down and buildings are erected and demolished. In the case of biological succession, a process akin to natural selection (see Evolution) is occurring: the ecosystem becomes home, in turn, to a number of different biological communities until (in the absence of outside interference) the one that is most suited or adapted to local conditions finally takes root. (That is, until it is replaced, and the process of succession continues.)

This most suited or adapted biological community is described as a *climax community,* one that has reached a stable point as a result of ongoing succession. In such a situation, the com-

munity is at equilibrium with environmental conditions, and conditions are stable, such that the biota experiences little change thereafter. The most significant forms of climax vegetation are often the defining characteristics of terrestrial biomes. (See Succession and Climax for more about this subject.)

DEFINING CHARACTERISTICS OF A BIOME

The boreal coniferous forest often is cited by biogeographers as a classic example of a biome, for a number of reasons. First, like most other terrestrial biomes, this one is defined by specific latitudinal positions: the term *boreal* means "northern," and these forests exist between 50 and 60 degrees north latitude. (Aside from the southernmost tip of South America and a few scattered islands, there is no significant landmass between 50 and 60 degrees south latitude.)

In North America the region between 50 and 60 degrees north latitude is the southerly band of Canadian provinces (Alberta and Saskatchewan, for example). The Eurasian equivalent of this region is a band encompassing the British Isles; an area of continental Europe that includes northern Germany, Poland, and southern Sweden; and a vast swath that spans the width of Russia from Saint Petersburg and Moscow in the west across the nation's wide expanse (10 time zones) to the Kamchatka peninsula north of Japan.

The boreal coniferous forest thus illustrates a key fact about biomes: they can occur in widely separated geographic regions as long as the environmental conditions are the same. In each of these locales average temperatures are low; summers are short, moist, and of moderate warmth; and winters are long, cold, and dry. Most precipitation is in the form of snow, and the A horizon of the soil, home of the organic material in which plants grow, is thin. Moreover, the soil is acidic and poor in nutrients. (See The Biosphere for more about soil.)

Most of the information conveyed in the preceding paragraph refers to the inorganic components of the boreal coniferous forest. (*Organic* does not necessarily mean "living," but it does refer to carbon-based chemical compounds other than carbonates, which are rocks, and carbon oxides, such as carbon dioxide.) As noted earlier, inorganic components of a biome include water and air, which in turn are involved in precipitation, weather, and climate. Although it does contain organic compounds from the decayed vegetable and animal matter that enriches it, soil, too, is largely inorganic, being formed from the weathering of rocks.

FLORA. Biomes are differentiated most clearly, however, on the basis of their organic components. The second term in the phrase *boreal coniferous* refers to a type of plant that produces cones containing seeds. Thus, the dominant plant life in the boreal coniferous forest includes evergreen conifers that can tolerate cold weather: pine, fir, and spruce.

The varieties that dominate may differ between geographic regions, however. The boreal coniferous forests of northeastern North America, for instance, are dominated by black spruce, while those in the northwest are characterized by stands of white spruce. In northeast Europe, Norway spruce is dominant, while species of pine and larch occupy the key positions in the forests of Siberia. Despite these differences in dominant species, the conditions are much the same, not only in terms of inorganic environment but also with regard to flora and fauna. In most boreal coniferous forests, the canopy or upper layer is so thick that it allows little light through. The result is that the understory, or lower layers of vegetation, is very limited.

FAUNA. As for animal life, species in the boreal coniferous forest include bear, moose, wolf, lynx, deer, weasels, rabbits, beavers, and chipmunks. With a few local variations, this roster of animal life is typical in most such biomes, whether in British Columbia or western Europe or Siberia.

A biome constitutes a complex network of interactions among plants, animals, and their surroundings, such that certain animals depend, either directly or indirectly, on certain plants for their sustenance. An obvious example is the beaver's use of coniferous tree limbs and even trunks for building shelter. Even more fundamental to the functioning of ecosystems is the role of plants as food.

Although few animals actually feed off the needles or bark of conifers, they do eat from these trees in more indirect ways. The woodpecker, for instance, consumes bugs that live in a tree's bark. Then there are the many insects that live off conifer seeds (see Ecosystems and Ecology for a discussion of conifer, or gymnosperm, reproduc-

tion), and these bugs, in turn, serve as food for birds, which are the prey of larger carnivores. Furthermore, though the understory in boreal coniferous forests is not dense, it provides enough vegetation to meet the needs of deer, rabbits, and other herbivores.

Classifying Biomes

Earlier it was stated that there are "almost" 200 countries on Earth. It might seem strange that something like the number of countries could be so inexact, when it would seem to be a matter of very exact quantities, like the number of states in the United States. But defining sovereign nations is a bit more challenging. Obviously, the United States, Switzerland, and Japan are sovereign nations, but many another political entity exists in a gray area.

If the number of independent nations on Earth is so open to question, it would stand to reason that the number of basic biomes is as well. After all, nations typically are delineated by such things as borders, seats at the United Nations, currency, and so forth, whereas the boundaries between biomes are much less exact. Therefore, it would be futile to attempt to say exactly how many biomes there are on Earth, since the number varies according to interpretation.

terrestrial, aquatic, and other categories. One of the more useful methods for classifying biomes is that of the American ecologist Eugene Pleasants Odum (1913–), introduced in his *Fundamentals of Ecology* (1953). The classification scheme that follows is based on that of Odum, who divided biomes into terrestrial and aquatic. In the present context, biomes have been grouped into five categories: forest, nonforest, freshwater, marine, and anthropogenic. The last of these categories refers to biomes strongly influenced by humans and their activities, though it should be noted that to some degree at least, human activities have influenced all of Earth's biomes. For example, many organisms carry in their fat cells trace amounts of human-manufactured contaminants, such as DDT. (See Food Webs for more on this subject.)

Biomes are organized here in such a way as to take into account their relative latitudes and corresponding climate. (Distinctions of latitude and climate are mostly relevant where terrestrial biomes are concerned.) As with biomes, there are many possible climate zones, particularly when rainfall patterns and other variables are considered. All climate zones, however, fall into one of three basic categories: tropical and subtropical, temperate, and polar and subpolar.

The first of these categories is a term comprising the region along the equator, extending north and south by about 30 degrees in either direction. In North America this would include southern Florida, Texas, and Louisiana. Temperate zones reach from about 30 to 60 degrees on either side of the equator, thus taking in most of the United States and southern Canada. Finally, subpolar and polar regions lie between 60 degrees and the poles, which are at 90 degrees.

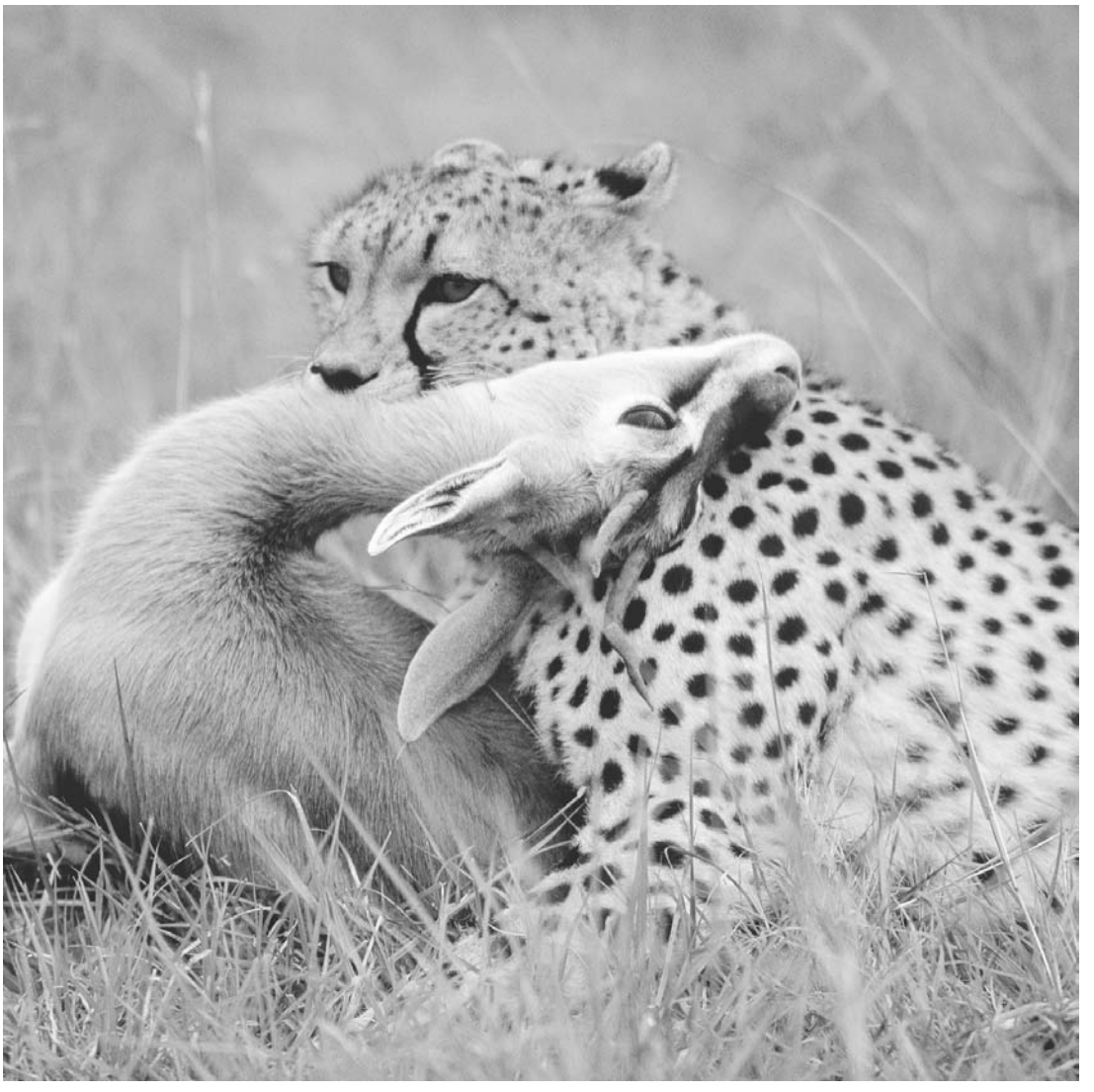
Real-Life Applications

Forest Biomes

The term *forest,* as used in the realm of ecology, is one of those rare words that means the same thing within a scientific context as it does in the everyday world. An ecologist or biogeographer would define *forest* in more or less the same way that a nonscientist would: as any ecosystem dominated by tree-size woody plants. Of course, numerous other characteristics and parameters, such as weather, altitude, and dominant species, further characterize types of forests.

boreal coniferous forests. Starting with the most northerly of forest biomes, there is the boreal coniferous forest, which we have discussed. Called *taiga* in Russia, boreal coniferous forests often are bordered on the north by tundra, discussed later in the context of nonforest ecosystems. An important subset of the boreal coniferous grouping is the montane forest, which also is dominated by conifers but which most often is found on mountains, at subalpine altitudes where the climate is cool and moist.

In addition to the dominant conifers, boreal coniferous forests also have important broadleafed angiosperms (plants that flower during sexual reproduction), including aspen, birch, poplar, and willow species. These forests are typically subject to periodic catastrophes, which result in at least partial destruction of the dominant trees within stands if not across a given forest as a whole. Among these catastrophic events are wildfires as well as defoliation by such pests as the spruce budworm.



Tropical grassland and savanna biomes, primarily in Africa, are best characterized by the extraordinarily abundant and diverse animal life, which includes such large mammals as the cheetah and the gazelle. *(© Kevin Schafer/Corbis. Reproduced by permission.)*

TEMPERATE DECIDUOUS FORESTS. Moving farther away from the poles, the next major forest biome is that of the temperate deciduous forest. The average American, especially on the East Coast, is likely to be more familiar with the temperate deciduous forest than with any other biome. This type of forest develops in a climate that is relatively moist, with winters that are fairly cold. The larger grouping of temperate deciduous forests is divided into smaller categories depending on the relative amount of annual rainfall.

The term *deciduous* refers to a tree that sheds its leaves seasonally, and these forests are dominated by such trees, broad-leafed species that include ash, basswood, birch, cherry, chestnut, dogwood, elm, hickory, magnolia, maple, oak, and walnut, among others. (Note that many of these species are angiosperms. Likewise, most coniferous trees are gymnosperms, or plants that reproduce sexually through exposed seeds as opposed to seeds hidden in a flower.) Among the varieties of animal life are squirrels, rabbits, skunks, opossums, deer, bobcat, timber wolves, foxes, and black bears.

TEMPERATE RAIN FORESTS. Temperate rain forests are not necessarily farther from the poles than temperate deciduous forests, but they are subject to milder winters. For example, the temperate rain forests of Washington

State are north of many a temperate deciduous forest on the East Coast, but owing to differences in climate patterns, they are subject to milder winters than those typical of the deciduous forests to the east.

Characterized by abundant precipitation (most of it rain rather than snow, due to the milder temperatures), these systems are very moist—as the "rain forest" in their name implies. This, in turn, means that they are seldom subject to catastrophic wildfires, and therefore they often attain the climax stage of old-growth forests. In the temperate rain forest, coniferous trees are dominant, and many of these trees are extremely large and old. Among the tree species typical of this biome are Douglas fir, hemlock, cedar, redwood, spruce, and yellow cypress.

Tropical forests are discussed at some length in the essays Ecosystems and Ecology as well as The Biosphere. Among the two most basic varieties of this biome are semi-evergreen tropical forests and evergreen tropical rain forests. Most of the Amazon rain forest in South America, for instance, is an evergreen tropical forest, while surrounding biomes are semi-evergreen. Much the same is true of biomes in central and southern Africa, such as that surrounding the Congo River, with evergreen forests closest to the river and semi-evergreen ones in nearby areas.

The tropics, in general, are characterized not by the four seasons of the more temperate climate zones, but by a dry season and a wet season. The environment of a semi-evergreen tropical forest is one that is subject to great extremes of wet and dry, meaning that water is not available in abundance year-round. This means that most trees and shrubs in the biome are seasonally deciduous, shedding their leaves in anticipation of the drier season. In an evergreen tropical rain forest, on the other hand, rainfall is frequent and regular, so there is no seasonal drought. Deciduous trees may drop their leaves at various times of year, depending on the species, but with a wet climate and a wide range of trees, there is always something in bloom.

As with the temperate rain forest, the tropical variety experiences little in the way of wildfire or other catastrophic disturbances, and therefore an old-growth, climax community often develops in this biome. For this reason, tropical rain forests usually contain a wide diversity of trees, an enormous richness of species, and an extraordinary range of animals and microorganisms. Though biogeographers and ecologists often use the boreal coniferous forest as an example when examining biomes, those northerly forests are hardly examples of biological diversity. On the other hand, the tropical rain forest represents such diversity to its greatest extent.

Nonforest Biomes

Making an abrupt shift from the lush world of the tropical rain forest, let us look now at the tundra: a cold, treeless biome in the arctic and subarctic regions. (The Arctic Circle lies at approximately 66.5 degrees north latitude. Lands north of that line include northern Alaska and Canada, most of Greenland, extreme northern Scandinavia, and a northern strip of Russia and Siberia. The subarctic region, less clearly defined, comprises simply those lands that lie directly below the Arctic Circle.) Characterized by a short growing season, the tundra experiences very little precipitation in the form of liquid water. Yet the soil may well be marshy because temperatures are too low for significant evaporation and because the ground is usually frozen solid, preventing drainage.

In the most northerly tundras the dominant plants are small, hardy species that grow no more than 2–4 in. (5–10 cm) tall. In subarctic regions the dominant shrub species may grow as tall as 3.28 ft. (1 m), and the marshiest subarctic tundra may be home to sedge and cotton grass meadows. Among the larger forms of animal life on the tundra are the caribou and musk ox as well as the wolf, one of the larger predatory species.

Grasslands and chaparral. Temperate grasslands are known as prairies in North America and steppes in Eurasia, and these grasslands often are divided into smaller subgroups depending on the height of the dominant grasses. Fire, aided by the dry climate, acts as a curb to prevent the tall grass from giving way to larger trees and forests. In the United States, however, so much prairie has been converted to agricultural or other anthropogenic purposes that it constitutes an endangered biome.

Much further south are the tropical grassland and savanna biomes that appear primarily in Africa. Although they do have scattered trees and shrubs, these biomes are dominated by grasses and other plants. In any case, the plant life



One type of freshwater biome is the swamp forest, which may be flooded either seasonally or permanently and is notable for its animal life, including heron and other bird species. *(© S. R. Maglione. Photo Researchers. Reproduced by permission.)*

is not what best characterizes this biome in the minds of most people. Rather, it is the extraordinarily abundant and diverse animal life, which includes such large mammals as the rhinoceros, elephant, hippopotamus, buffalo, cheetah, gazelle and other antelope, wild dog, and hyena. Then, of course, there is the lion, "king of beasts," sometimes incorrectly portrayed (for instance, in many *Tarzan* movies) as a jungle creature.

A biome typical of coastal southern California, the chaparral is distinguished by what often is described as a Mediterranean climate: dry, rainy in winter, and prone to drought in summers. The characteristic plant in a chaparral region has thick, leathery leaves that help it preserve moisture during the dry seasons. As with most other nonforest biomes, wildfire is a major controlling factor.

DESERT. Deserts, discussed in more detail within The Biosphere, constitute a biome that may be temperate or tropical and which usually appears near the center of a continent. Such is particularly the case with the Gobi and Taklimakan deserts in northwestern and southwestern China, respectively; both deserts are located almost as far away from ocean as it is possible to be on Earth. Deserts also may occur in "rain shadows," areas separated from oceans by high mountains.

The unavailability of water is the chief defining feature of the desert, a biome that receives less than 9.9 in. (25 cm) of precipitation per year. Extremely dry deserts support virtually no plant productivity and therefore little, if any, animal life either. Such is the case, for instance, with the extraordinarily forbidding desert known as Rub' al Khali ("The Empty Quarter"), which occupies the lower third of the Arabian peninsula. On the other hand, less dry deserts may support relatively diverse plant life, as is the case, for instance, in Arizona.

Freshwater Biomes

Now we make another abrupt shift, in this case from the dry desert to aquatic biomes, beginning with the freshwater variety. Among these are lentic biomes, which appear in the area of lakes and ponds—any place where water is still. (This would include even a vast body of water such as Lake Superior, which, though it looks like a sea from the edge, and experiences waves and heavy swells, is nonetheless a freshwater body where water is not flowing. Hence, it is by definition a lentic environment.) The water in these bodies

may take a few days to flush; on the other hand, it may take centuries. By sitting for such long periods of time, the water may accumulate large amounts of nutrients, and this is one of the variables whereby subgroups of the lentic biome are classified.

In a lotic biome, such as that of a river or stream, water is flowing. A lotic biome may be as small as a babbling brook that runs for less than a mile, or as great as the Mississippi River, which drains much of the continental United States. Where lotic biomes are concerned, the greatest variables involve the strength of the flow, including its quantity, velocity, and seasonal variations. These characteristics influence other aspects of the ecosystem: for example, if water flows calmly and slowly, the bottom tends to gather silt. This provides a habitat for certain small species, such as the crustacean, known variously as a crayfish, crawfish, or crawdaddy.

A lotic environment is not fully self-sustaining, and therefore it may not qualify as a true biome. Though they support some plant life, these ecosystems do not have a full complement of autotrophs, or life-forms (usually plants) that depend only on the Sun and the atmosphere, rather than other organisms, for sustenance. Usually, the lotic ecosystem relies on the input of organic matter from the nearby terrestrial environment or from lakes upstream or both. These other biomes provide the lotic biome with the nutrients necessary to feed its fish and other aquatic species.

WETLANDS. Yet another freshwater biome is that of the wetlands. Just as rain forests were known as *jungles* until ecology and environmentalism entered the mainstream in the 1970s, so the term *wetlands* replaced a more blunt-sounding word: *swamp.* That word and several other old-fashioned ones are preserved in the terms for the four major wetland types: marsh, swamp forest, bog, and fen. Regardless of the name, this is a biome found in shallow waters, often in regions known for their pronounced seasonal variations of water depth.

The most biologically productive wetlands, marshes typically are dominated by relatively tall angiosperm varieties, such as the reed, cattail, and bulrush, as well as by floating flowers, such as the water lily and lotus. Swamp forests, such as the Okeefenokee on the Georgia-Florida border, are heavily populated with trees that include bald cypress and silver maple and may be flooded either seasonally or permanently. The Okeefenokee is notable for its animal life: not just heron and other bird species but also some of the more terrifying reptilian forms, including alligators and water moccasins, for which swamps are notorious.

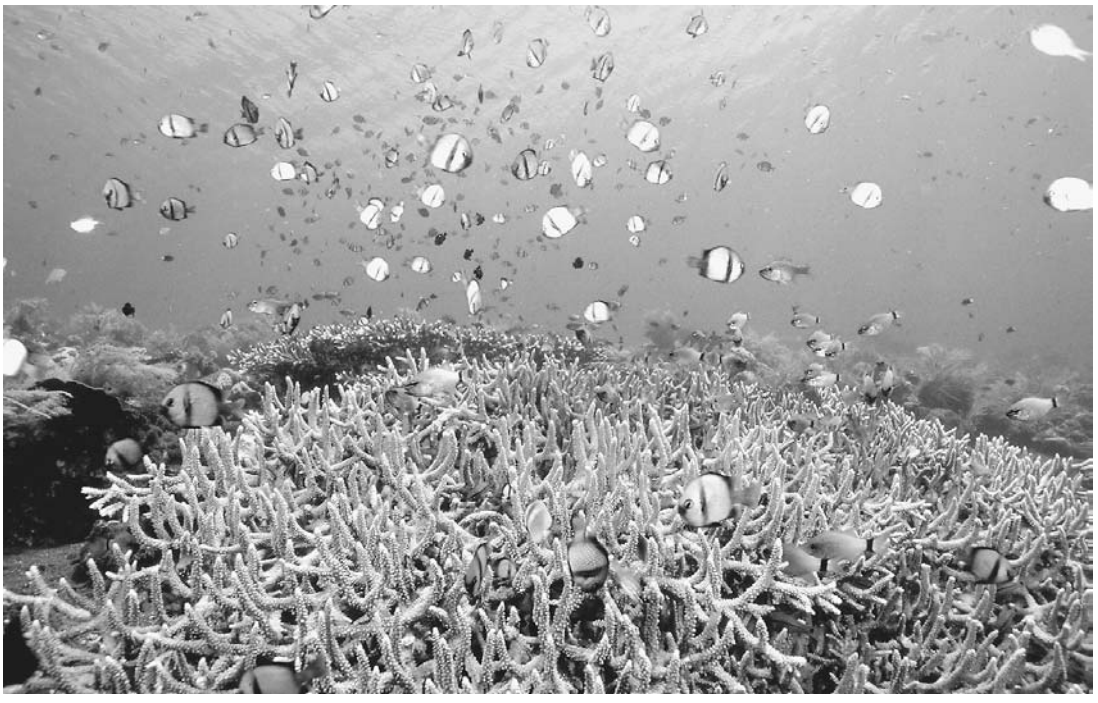
Much less biologically productive than either marshes or swamps are bogs, which generally have acidic soil that supports only a limited range of vegetation. Characterized by a cool, wet climate (many of them are found in England), bogs often are dominated by sphagnum moss of one species or another. Later, when the sphagnum moss dies and the remains of several generations are compacted together with other plant debris, this becomes the basis for peat, which provides fuel for some homes in the British Isles and Europe.

Finally, there is the fen, another wetland found throughout the British Isles. Fens resemble bogs in several ways, including the fact that the local climate is usually cold (unlike the swamp forest, where the climate is generally hot). The fen has a better nutrient supply than the bog, however, and consequently the soil is less acidic, meaning that the biome as a whole is more productive.

Marine Biomes

The largest biome, geographically, is that of the open ocean, sometimes called a *pelagic oceanic biome.* Yet in terms of primary productivity—the first level in the food web—the ocean might as well be a desert. Tossed by waves and tides and heavily affected by the powerful salt content in its chemistry, the open ocean depends for its primary productivity not on plants but on phytoplankton, microscopic organisms that include a range of bacteria and algae.

Small crustaceans known as zooplankton eat the phytoplankton, only to be consumed, in turn, by small fish. Thus it goes up the trophic levels of the oceanic food web to the largest predators: bluefin tuna, sharks, squid, and whales. At the bottom of the ocean are other ecosystems, which depend on the slow rain of dead organic matter, or biomass, from the surface. Little is known about the deep-ocean biomes, but they appear to be diverse, if low in productivity (i.e., they have a relatively wide range of species but a small number of individuals).



Coral reefs appear only in tropical regions. The principal characteristic of this biome is its substrate of calcium carbonate, formed from the exoskeletons of dead coral polyps and other creatures. On this structure is built a highly productive biome in which coral, algae, fish, and invertebrates thrive. *(© Andrew Martinez. Photo Researchers. Reproduced by permission.)*

Upwelling regions are relatively deep, nutrient-rich areas that sustain highly productive biomes. Among the large variety of species included in such biomes are fish and shark, marine mammals, and birds such as gulls. Upwellings off the west coast of South America and in the Antarctic Ocean provide some of the human world's most abundant fisheries.

CLOSER TO SHORE. Closer to the major landmasses are the biomes of the continental shelves. There the water is warm compared with that of the open ocean, and the nutrient supply is relatively high. This flow of nutrients is fed partly by rivers that empty into the seas but also by the occasional rising of deeper, richer waters to the surface. Not surprisingly, then, phytoplankton and animal life are highly productive here, and continental shelf regions such as those of the Grand Banks off northeastern North America offer highly abundant and commercially important fisheries.

Another ocean biome closer to shore is that of the estuary, an ecosystem that is enclosed by land on several sides but is still open to the sea. Because they typically experience substantial inflows of river water from the nearby land, estuaries feature characteristics of both marine and freshwater biomes and offer highly productive ecosystems. Many a commercially important species of fish, shellfish, and crustacean makes its early home in an estuary before moving on to deeper waters after reaching maturity.

Seashores constitute a variety of oceanic biome or, indeed, several varieties. Environmental factors such as the intensity of wave motion determine the characteristics of the seashore biome, as do latitude. For example, temperate seashore ecosystems can develop kelp "forests." (See Succession and Climax for more about the interrelations of species in the kelp forest.) In other areas, where the bottoms are soft and covered with sand or mud, dominant species include mollusks, crustaceans, and marine worms.

As with seashores, coral reefs are those rare oceanic biomes affected by latitude; in fact, this type of biome appears only in tropical regions. The principal characteristic of the coral reef is its substrate of calcium carbonate, formed from the exoskeletons of dead coral polyps and other creatures. On this structure is built a highly productive biome in which coral, algae, fish, and invertebrates (animals without a backbone) thrive.

KEY TERMS

ABUNDANCE: A measure of the degree to which an ecosystem possesses large numbers of particular species. An abundant ecosystem may or may not have a wide array of different species. Compare with *complexity.*

ALPINE: A term that refers to a biogeographic zone that includes mountain slopes above the timberline.

ANGIOSPERM: A type of plant that produces flowers during sexual reproduction.

ANTHROPOGENIC: Influenced by human activity.

BIOGEOGRAPHY: The study of the geographic distribution of plants and animals, both today and over the course of extended periods.

BIOLOGICAL COMMUNITY: The living components of an ecosystem.

BIOME: A large ecosystem, characterized by its dominant life-forms. There are two basic varieties of biome: terrestrial, or land-based, and aquatic.

BIOTA: A combination of all flora and fauna (plant and animal life, respectively) in a region.

CANOPY: The upper portion or layer of the trees in a forest. A forest with a closed canopy is one so dense with vegetation that the sky is not visible from the ground.

CARNIVORE: A meat-eating organism, or an organism that eats *only* meat (as distinguished from an omnivore).

CLIMAX: A theoretical notion intended to describe a biological community that has reached a stable point as a result of ongoing succession. In such a situation, the community is at equilibrium with environmental conditions, and conditions are stable, such that the biota experiences little change thereafter.

COMPLEXITY: The range of ecological niches within a biological community. The degree of complexity is the number of different species that theoretically *could* exist in a given biota, as opposed to its diversity, or actual range of existing species.

CONIFER: A type of tree that produces cones bearing seeds.

DECIDUOUS: A term for a tree or other form of vegetation that sheds its leaves seasonally.

DECOMPOSERS: Organisms that obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. The principal forms of decomposer are bacteria and fungi.

Anthropogenic Biomes

Finally, there are anthropogenic biomes, such as the urban-industrial techno-ecosystem found in many a large metropolitan area. Such an ecosystem may include many species in addition to humans, but these—pets, houseplants, and the like—are not always native to the region, and probably would not flourish unless returned to their native biomes. New York City would be perhaps the ultimate example of an urban-industrial techno-ecosystem. Though it is far from a natural environment, it teems with life, from the oaks and elms in Central Park to the rats of the sewers, and from the pigeons that peck at crumbs on the sidewalks to the houseplants on the balconies and fire escapes of apartment buildings.

KEY TERMS CONTINUED

DETRITIVORES: Organisms that feed on waste matter, breaking organic material down into inorganic substances that then can become available to the biosphere in the form of nutrients for plants. Their function is similar to that of decomposers; however, unlike decomposers—which tend to be bacteria or fungi—detritivores are relatively complex organisms, such as earthworms or maggots.

DIVERSITY: A measure of the number of different species within a biological community.

ECOLOGY: The study of the relationships between organisms and their environments.

ECOSYSTEM: A community of interdependent organisms along with the inorganic components of their environment.

FAUNA: Animals.

FLORA: Plants.

FOOD WEB: A term describing the interaction of plants, herbivores, carnivores, omnivores, decomposers, and detritivores in an ecosystem. Each of these consumes nutrients and passes them along to other organisms (or, in the case of the decomposer food web, to the soil and environment). The food web may be thought of as a bundle or network of food chains, but since the latter rarely exist separately, scientists prefer the concept of a food web to that of a food chain.

FOREST: In general terms, a forest is simply any ecosystem dominated by tree-size woody plants. A number of other characteristics and parameters (for example, weather, altitude, and dominant species) further define types of forests, such as tropical rain forests.

GYMNOSPERM: A type of plant that reproduces sexually through the use of seeds that are exposed, not hidden in an ovary, as with an angiosperm.

HERBIVORE: A plant-eating organism.

OMNIVORE: An organism that eats both plants and other animals.

ORGANIC: At one time chemists used the term *organic* only in reference to living things. Now the word is applied to most compounds containing carbon, with the exception of carbonates (which are minerals), and oxides, such as carbon dioxide.

SUCCESSION: The progressive replacement of earlier biological communities with others over time.

TERRESTRIAL: Land-based.

UNDERSTORY: Layers of vegetation below the canopy in a forest.

Another anthropogenic biome is the rural techno-ecosystem, which is not as removed from human civilization as the "rural" in its name would imply. This type of biome appears in regions around transportation and transmission corridors, including highways, railways, canals, and aqueducts, as well as alongside power and telephone lines. Small towns are a characteristic area for such a biome, as are the regions around coal mines and other industrial plants devoted to the extraction, processing, or manufacture of products from natural resources. This biome usually supports a mixture of introduced species and native species, the latter being those varieties that can survive the disturbances, pollution, and other stresses associated with the human pres-

ence. For example, in the woods along an interstate highway, there are bound to be omnivorous creatures such as raccoons, which thrive on litter thrown out of passing cars. Such creatures must be agile enough to survive the threat of becoming "road kill," as well as other hazards associated with the environment. As with the city biome, the rural techno-ecosystem includes plenty of life-forms that have been introduced artificially, an example being the wildflowers planted on a median by state highway workers.

Agro-ecosystems are ecosystems that are managed and harvested for human use: farms, orchards, fisheries, commercial forests, and other agricultural concerns. Here the defining characteristic is the level of management, or the degree of anthropogenic influence. Very heavily managed agro-ecosystems involve the planting of non-native crop species and the introducing of non-native plants, often to the exclusion of native species. The "crop" may be a herd of animals, as when western ranchers introduced non-native cattle, and in the process killed off native predators such as coyotes. On the other hand, there are less heavily managed agro-ecosystems that do allow native wildlife species to thrive alongside those species introduced for commercial purposes.

WHERE TO LEARN MORE

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BIOLOGICAL COMMUNITIES

SYMBIOSIS

BIOLOGICAL COMMUNITIES

SUCCESSION AND CLIMAX

SYMBIOSIS

CONCEPT

Symbiosis is a biological relationship in which two species live in close proximity to each other and interact regularly in such a way as to benefit one or both of the organisms. When both partners benefit, this variety of symbiosis is known as *mutualism.* The name for a situation in which only one of the partners benefits is far more well known. Such an arrangement is known as *parasitism,* and a parasite is an organism that obtains nourishment or other life support from a host, usually without killing it. By their very nature, parasites are never beneficial, and sometimes they can be downright deadly. In addition to the extremes of mutualism and parasitism, there is a third variety of symbiosis, called *commensalism.* As with parasitism, in a relationship characterized by commensalism only one of the two organisms or species derives benefit, but in this case it manages to do so without causing harm to the host.

HOW IT WORKS

Varieties of Symbiosis

When two species—that is, at least two individuals representing two different species—live and interact closely in such a way that either or both species benefit, it is symbiosis. It is also possible for a symbiotic relationship to exist between two organisms of the same species. Organisms engaging in symbiotic relationships are called symbionts.

There are three basic types of symbiosis, differentiated as to how the benefits (and the detriments, if any) are distributed. These are commensalism, parasitism, and mutualism. In the first two varieties, only one of the two creatures benefits from the symbiotic relationship, and in both instances the creature who does not benefit—who provides a benefit to the other creature—is called the host. In commensalism the organism known as the commensal benefits from the host without the host's suffering any detriment. By contrast, in parasitism the parasite benefits at the expense of the host.

MUTUALISM: HUMAN AND DOG. Mutualism is distinguished from the other two types of symbiosis, because in this variety both creatures benefit. Thus, there is no host, and theoretically the partners are equal, though in practice one usually holds dominance over the other. An example of this inequality is the relationship between humans and dogs. In this relationship, both human and dog clearly benefit: the dog by receiving food, shelter, and care and the human by receiving protection and loving companionship—the last two being benefits the dog also receives from the human. Additionally, some dogs perform specific tasks, such as fetching slippers, assisting blind or disabled persons, or tracking prey for hunting or crime-solving purposes.

For all this exchange of benefits, one of the two animals, the human, clearly holds the upper hand. There might be exceptions in a few unusual circumstances, such as dog lovers who are so obsessive that they would buy food for their dogs before feeding themselves. Such exceptions, however, are rare indeed, and it can be said that in almost all cases the human is dominant.

Obligate and Facultative Relationships

Most forms of mutualism are facultative, meaning that the partners can live apart successfully.

Some relationships of mutualism are so close that the interacting species are unable to live without each other. A symbiotic relationship in which the partners, if separated, would be unable to continue living is known as an *obligate* relationship. In commensalism or parasitism, the relationship is usually obligate for the commensal or the parasite, since by definition they depend on the host. At the same time, and also by definition, the host is in a facultative relationship, since it does not need the commensal or parasite—indeed, in the case of the parasite, would be much better off without it. It is possible, however, for an organism to become so adjusted to the parasite attached to its body that the sudden removal of the parasite could cause at least a short-term shock to the system.

Inquilinism

A special variety of commensalism is inquilinism, in which the commensal species makes use of the host's nest or habitat, without causing any inconvenience or detriment to the host. Inquilinism (the beneficiary is known as an inquiline) often occurs in an aquatic environment, though not always. In your own yard, which is your habitat or nest, there may be a bird nesting in a tree. Supposing you benefit from the bird, through the aesthetic enjoyment of its song or the pretty colors of its feathers—in this case the relationship could be said to be a mutualism. In any case, the bird still benefits more, inasmuch as it uses your habitat as a place of shelter.

The bird example is an extremely nonintrusive case of inquilinism; more often than not, however, a creature actually uses the literal nest of another species, which would be analogous to a bird nesting in your attic or even the inside of your house. This is where the analogy breaks down, of course, because such an arrangement would no longer be one of commensalism, since you would be suffering a number of deleterious effects, not the least of which would be bird droppings on the carpet.

Inquilinism sometimes is referred to as a cross between commensalism and parasitism and might be regarded as existing on a continuum between the two. Certainly, there are cases of a creature making use of another's habitat in a parasitic way. Such is the case with the North American cowbird and the European cuckoo, both of which leave their offspring in the nests of other birds to be raised by them. (See Instinct and Learning for a discussion of how these species exploit other birds' instinctive tendency to care for their young.)

REAL-LIFE APPLICATIONS

Mycorrhizae

One of the best examples of mutualism is known by the unusual name mycorrhiza, which is a "fungus root," or a fungus living in symbiosis with the roots of a vascular plant. (A vascular plant is any plant species containing a vascular system, which is a network of vessels for moving fluid through the body of the organism.) The relationship is a form of mutualism because, while the fungus benefits from access to carbohydrates, proteins, and other organic nutrients excreted by or contained in the roots of the host plant, the host plant benefits from an enhanced supply of inorganic nutrients, especially phosphorus, that come from the fungus.

The fungus carries out this function primarily by increasing the rate at which organic matter in the immediate vicinity of the plant root decomposes and by efficiently absorbing the inorganic nutrients that are liberated by this process-nutrients it shares with the plant. (The term *organic* refers to the presence of carbon and hydrogen together, which is characteristic not only of all living things but of many nonliving things as well.) The most important mineral nutrients that the fungus supplies to the plant are compounds containing either phosphorus or, to a lesser degree, nitrogen. (These elements are present in biogeochemical cycles—see The Biosphere.) So beneficial is the mycorrhizal mutualism that about 90% of all vascular plant families, including mustards and knotweeds (family *Brassicaceae* and *Polygonaceae,* respectively), enjoy some such relationship with fungi.

SOME EXAMPLES OF MYCORRHIZAE. Many mycorrhizal fungi in the *Basiodiomycete* group develop edible mushrooms, which are gathered by many people for use in gourmet cooking. Mushroom collectors have to be careful, of course, because some mycorrhizal fungi are deadly poisonous, as is the case with the death angel, or destroying angel—*Amanita virosa.*

Perhaps the most famous of the edible mushrooms produced by mycorrhizae are the many varieties known by the name truffle. Among these mushrooms is *Tuber melanosporum,* which is commonly mycorrhizal on various species of oak tree. The spore-bearing bodies of the truffle fungi develop underground and are usually brown or black and covered with warts. Truffle hunters require the help of truffle-sniffing pigs or dogs, but their work is definitely worth the trouble: good truffles command a handsome price, and particularly in France the truffle industry is big business. Given the lucrative nature of the undertaking, one might ask why people do not cultivate truffles rather than hunting for them. To create the necessary conditions for cultivation, however, so much effort is required that it is difficult to make a profit, even at the high prices charged for truffles. The soil composition must be just right, and under conditions of cultivation this takes about five years.

Orchids are an example of a plant in an obligate mutualism: they can thrive only in a mycorrhizal relationship. Tiny and dustlike, orchid seeds have virtually no stored energy to support the seedling when it germinates, or begins to grow. Only with the assistance of an appropriate mycorrhizal fungus can these seedlings begin developing. Until horticulturists discovered this fact, orchids were extremely difficult to propagate and grow in greenhouses; today, they are relatively easy to breed and cultivate.

THE IMPORTANCE OF MYCORRHIZAE. Some species of vascular plants do not contain chlorophyll, the chemical necessary for photosynthesis, or the conversion of light energy from the Sun into usable chemical energy in a plant. Such a plant is like a person missing a vital organ, and under normal circumstances, it would be impossible for the plant to survive. Yet the Indian pipe, or *Monotropa uniflora,* has managed to thrive despite the fact that it produces no chlorophyll; instead, it depends entirely on mycorrhizal fungus to supply it with the organic nutrients it needs. This obligate relationship is just one example of the critical role mycorrhizae perform in the lives of plants throughout the world.

Mycorrhizae are vital to plant nutrition, especially in places where the soil is poor in nutrients. Whereas many plant roots develop root hairs as a means of facilitating the extraction of water and nutrients from the soil, plant roots



ONE OF THE BEST EXAMPLES OF MUTUALISM IS THE MYCORRHIZA, A FUNGUS LIVING IN SYMBIOSIS WITH THE ROOTS OF A VASCULAR PLANT. MANY MYCORRHIZAL FUNGI DEVELOP EDIBLE MUSHROOMS, SUCH AS THE TRUFFLE, USED IN GOURMET COOKING. *(© Owen Frnaken/Corbis. Reproduced by permission.)*

that have a mycorrhizal fungus usually do not. Instead, these plants rely heavily on the fungus itself to absorb moisture and vital chemical elements from the ground. This means that it may be difficult or impossible for plants to survive if they are removed from an environment containing mycorrhizal fungus, a fact that indicates an obligate relationship.

Often, when species of trees and shrubs grown in a greenhouse are transplanted to a nonforested outdoor habitat, they exhibit signs of nutritional distress. This happens because the soils in such habitats do not have populations of appropriate species of mycorrhizal fungi to colonize the roots of the tree seedlings. If, however, seedlings are transplanted into a clear-cut area that was once a forest dominated by the same or closely related species of trees, the plants generally will do well. This happens because the clear-cut former forest land typically still has a population of suitable mycorrhizal fungi.

Plants' dependence on mycorrhizal fungi may be so acute that the plants do not do well in the absence of such fungi, even when growing in soil that is apparently abundant in nutrients.

Although most mycorrhizal relationships are not so obligate, it is still of critical important to consider mycorrhizal fungi on a site before a natural ecosystem is converted into some sort of anthropogenic habitat (that is, an area dominated by humans—see Biomes). For example, almost all the tree species in tropical forests depend on mycorrhizae to supply them with nutrients from the soils, which are typically infertile. (See The Biosphere for more about the soil in rain forests.) If people clear and burn the forest to develop new agricultural lands, they leave the soil bereft of a key component. Even though some fungi will survive, they may not necessarily be the appropriate symbionts for the species of grasses and other crops that farmers will attempt to grow on the cleared land.

Interkingdom and Intrakingdom Partnerships

Mycorrhizae are just one example of the ways that mutualism brings into play interactions between widely separated species—in that particular case, between members of two entirely different kingdoms, those of plant and fungi. In some cases, mutualism may bring together an organism of a kingdom whose members are incapable of moving on their own (plants, fungi, or algae) with one whose members are mobile (animals or bacteria). An excellent example is the relationship between angiosperm plants and bees, which facilitate pollination for the plants (see Ecosystems and Ecology.)

Another plant-insect mutualism exists between a tropical ant (*Pseudomyrmex ferruginea*) and a shrub known as the *bull's horn acacia* (*Acacia cornigera*). The latter has evolved hollow thorns, which the ants use as protected nesting sites. The bull's horn acacia has the added benefit, from the ant's perspective, of exuding proteins at the tips of its leaflets, thus providing a handy source of nutrition. In return, the ants protect the acacia both from competition with other plants (by removing any encroaching foliage from the area) and from defoliating insects (by killing herbivorous, or plant-eating, insects and attacking larger herbivores, such as grazing mammals).

A much less dramatic, though biologically quite significant, example of interkingdom mutualism is the lichen. Lichen is the name for about 15,000 varieties, including some that are incorrectly called *mosses* (e.g., reindeer moss). Before the era of microscopy, botanists considered lichens to be single organisms, but they constitute an obligate mutualism between a fungus and an alga or a blue-green bacterium. The fungus benefits from access to photosynthetic products, while the alga or bacterium benefits from the relatively moist habitat that fungus provides as well as from enhanced access to inorganic nutrients.

Big and small. In contrast to these cross-kingdom or interkingdom types of mutualism, there may be intrakingdom (within the same kingdom) symbiotic relationships between two very different types of animal. Often, mutualism joins forces in such a way that humans, observing these interactions, see in them object lessons, or stories illustrating the concept that the meek sometimes provide vital assistance to the mighty. One example of this is purely fictional, and it is a very old story indeed: Aesop's fable about the mouse and the lion.

In this tale a lion catches a mouse and is about to eat the little creature for a snack when the mouse pleads for its life; the lion, feeling particularly charitable that day, decides to spare it. Before leaving, the mouse promises one day to return the favor, and the lion chuckles at this offer, thinking that there is no way that a lowly mouse could ever save a fierce lion. Then one day the lion steps on a thorn and cannot extract it from his paw. He is in serious pain, yet the thorn is too small for him to remove with his teeth, and he suffers hopelessly—until the mouse arrives and ably extracts the thorn.

Many real-life examples of this strong-weak or big-small symbiosis exist, one of the more well-known versions being that between the African black rhinoceros (*Diceros bicornis*) and the oxpecker, or tickbird. The oxpecker, of the genus *Buphagus,* appears in two species, *B. africanus* and *B. erythrorhynchus.* It feeds off ticks, flies, and maggots that cling to the rhino's hide. Thus, this oddly matched pair often can be seen on the African savannas, the rhino benefiting from the pest-removal services of the oxpecker and the oxpecker enjoying the smorgasbord that the rhino's hide offers.

Humans and other species. Humans engage in a wide variety of symbiotic relationships with plants, animals, and bacteria. Bacteria may be parasitic on humans, but far



Intrakingdom symbiotic relationships can exist between two very different types of animal. The oxpecker, or tickbird, feeds off the ticks, flies, and maggots that cling to the hide of the African black rhinoceros. This oddly matched pair often can be seen on the African savannas. *(© Joe McDonald/Corbis. Reproduced by permission.)*

from all microorganisms are parasites: without the functioning of "good" bacteria in our intestines, we would not be able to process and eliminate food wastes properly. The relationship of humans to animals that provide a source of meat might be characterized as predation (i.e., the relationship of predator to prey), which is technically a form of symbiosis, though usually it is not considered in the same context. In any case, our relationship to the animals we have domesticated, which are raised on farms to provide food, is a mixture of predation and mutualism. For example, cows (*Bos taurus*) benefit by receiving food, veterinary services, and other forms of care and by protection from other predators, which might end the cows' lives in a much more unpleasant way than a rancher will.

All important agricultural plants exist in tight bonds of mutualism with humans, because human farmers have bred species so selectively that they require assistance in reproducing. For example, over time, agricultural corn, or maize (*Zea mays*), has been selected in such a way as to favor those varieties whose fruiting structure is enclosed in a leafy sheath that does not open and whose seeds do not separate easily from the supporting tissue. In other words, thanks to selective breeding, the corn that grows on farms is enclosed in a husk, and the kernels do not come off of the cob readily. Such corn may be desirable as a crop, but because of these characteristics, it is incapable of spreading its own seeds and thereby reproducing on its own. Obviously, agricultural corn is not on any endangered species list, the reason being that farmers continue to propagate the species through breeding and planting.

Another example of human-animal mutualism, to which we alluded earlier, is the relationship between people and their pets, most notably dogs (*Canis familiaris*) and house cats (*Felis catus*). Fed and kept safe in domestication, these animals benefit tremendously from their interaction with humans. Humans, in turn, gain from their pets' companionship, which might be regarded as a mutual benefit—at least in the case of dogs. (And even cats, though they pretend not to care much for their humans, have been known to indulge in at least a touch of sentimentality.) In addition, humans receive other services from pets: dogs protect against burglars, and cats eradicate rodents.

KEY TERMS

commensalism: A symbiotic relationship in which one organism, the commensal, benefits without causing any detriment to the other organism, the host.

facultative: A term for a symbiotic relationship in which partners are capable of living apart.

host: The term for an organism that provides a benefit or benefits for another organism in a symbiotic relationship of commensalism or parasitism.

inquilinism: A type of symbiosis in which one species, the inquiline, makes use of a host's nest or habitat without causing any detriment to the host. Inquilinism is considered a variety of commensalism.

obligative: A term for a symbiotic relationship in which the partners, if they were separated, would be incapable of continuing to live.

parasitism: A symbiotic relationship in which one organism, the parasite, benefits at the expense of the other organism, the host.

symbiosis: A biological relationship in which (usually) two species live in close proximity to one another and interact regularly in such a way as to benefit one or both of the organisms. Symbiosis may exist between two or more individuals of the same species as well as between two or more individuals representing two different species. The three principal varieties of symbiosis are *mutualism, commensalism,* and *parasitism.*

Symbiosis Among Insects

Where insects and symbiosis are involved, perhaps the ideas that most readily come to mind are images of parasitism. Indeed, many parasites are insects, but insects often interact with other species in relationships of mutualism, such as those examples mentioned earlier (bees and angiosperms, ants and bull's horn acacia plants). Additionally, there are numerous cases of mutualism between insect species. One of the most intriguing is the arrangements that exists between ants and aphids, insects of the order *Homoptera,* which also are known as plant lice.

In discussing the ant-aphid mutualism, scientists often compare the aphids to cattle, with the ants acting as protectors and "ranchers." What aphids have that ants want is something called honeydew, a sweet substance containing surplus sugar from the aphid's diet that the aphid excretes through its anus. In return, ants protect aphid eggs during the winter and carry the newly hatched aphids to new host plants. The aphids feed on the leaves, and the ants receive a supply of honeydew.

In another mutualism involving a particular ant species, *Formica fusca,* two organisms appear to have evolved together in such a way that each benefits from the other, a phenomenon known as coadaptation. This particular mutualism involves the butterfly *Glaucopsyche lygdamus* when it is still a caterpillar, meaning that it is in the larval, or not yet fully developed, stage. Like the aphid, this creature, too, produces a sweet "honeydew" solution that the ants harvest as food. In return, the ants defend the caterpillar against parasitic wasps and flies.

When mutualism also can be parasitism. As the old saying goes, "One man's meat is another man's poison"—in other words, what is beneficial to one person may be harmful to another. So it is with symbiotic relationships, and often a creature that plays a helpful, mutualistic role in one relationship may be a harmful parasite in another interaction. Aphids, for instance, are parasitic to many a host plant, which experiences yellowing, stunting, mottling, browning, and curling of leaves as well as inhibiting of its ability to produce crops.

One particular butterfly group, *Heliconiinae* (a member of the *Nymphalidae,* largest of the butterfly families) furnishes another example of the fact that a mutualistic symbiont, in separate interaction, can serve as a parasite. Moreover, in this particular case the heliconius butterfly can be a mutualistic symbiont and parasite for the very same plant. Heliconius butterflies scatter the

pollen from the flowers of passionflower vines (genus *Passiflora*), thus benefiting the plant, but their females also lay eggs on young *Passiflora* shoots, and the developing larva may eat the entire shoot. As an apparent adaptive response, several *Passiflora* species produce new shoots featuring a small structure that closely resembles a heliconius egg. A female butterfly that sees this "egg" will avoid laying her own egg there, and the shoot will be spared.

COMMENSALISM

Years ago a *National Geographic* article on the Indian city of Calcutta included a photograph that aptly illustrated the idea of commensalism, though in this case not between animals or plants but between people. The photograph showed a street vendor in a tiny wooden stall with a window, through which he sold his wares to passers-by. It was a rainy day, and huddled beneath the window ledge (which also served as a countertop) was another vendor, protecting himself and his own tray of goods from the rain.

The photograph provided a stunning example, in microcosm, of the overpopulation problem both in Calcutta and in India as a whole—a level of crowding and of poverty far beyond the comprehension of the average American. At the same time it also offered a beautiful illustration of commensalism (though this was certainly not the purpose of including the picture with the article). The vendor sitting on the ground acted in the role of commensal to the relatively more fortunate vendor with the booth, who would be analogous to the host.

The relationship was apparently commensal, because the vendor on the ground received shelter from the other vendor's counter without the other vendor's suffering any detriment. If the vendor in the booth wanted to move elsewhere, and the vendor on the ground somehow prevented him from doing so, then the relationship would be one of parasitism. And, of course, if the vendor with the booth charged his less-fortunate neighbor rent, then the relationship would not be truly commensal, because the vendor on the ground would be paying for his shelter. To all appearances, however, the interaction between the two men was perfectly commensal.

COMMENSALISM IN NATURE. Plants that grow on the sides of other plants without being parasitic are known as *epiphytic plants.* Among these plants are certain species of orchids, ferns, and moss. By "standing on the shoulders of giants," these plants receive enormous ecological benefits: the height of their hosts gives them an opportunity to reach a higher level in the canopy (the upper layer of trees in the forest) than they would normally attain, and this provides them with much greater access to sunlight. At the same time, the hosts are not affected either negatively or positively by this relationship.

Another commensal relationship, known as *phoresy,* is a type of biological hitchhiking in which one organism receives access to transportation on the body of another animal, without the transporting animal being adversely affected by this arrangement. The burdock (*Arctium lappa*) is one of several North American plant species that produce fruit that adheres to fur and therefore is dispersed easily by the movement of mammals. The burdock is special from a human standpoint, however, inasmuch as the anatomical adaptation that makes possible its adhesion to fur provided designers with the model for that extremely useful innovation, Velcro.

As with the illustration of the street vendors in Calcutta, it is always possible that commensalism, through a slight alteration, may yield a relationship in which the host is affected negatively. There are instances in which individual animals may become loaded heavily with sticky fruit from the burdock (or other plants that employ a similar mechanism), thus causing their fur to mat excessively and perhaps resulting in significant detriment. This is not common, however, and usually this biological relationship is truly commensal. Furthermore, phoresy should not be confused with parasitic relationships in which a creature such as a tick attaches itself to the body of another organism for transport or other purposes. (For much more about parasitism, see Parasites and Parasitology.)

WHERE TO LEARN MORE

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BIOLOGICAL COMMUNITIES

CONCEPT

An ecosystem is a complete community of interdependent organisms as well as the inorganic components of their environment; by contrast, a biological community is just the living members of an ecosystem. Within the study of biological communities there are a great number of complexities involved in analyzing the relationships between species as well as the characteristics of specific communities. Yet many of the concepts applicable to biological communities as a whole also apply to human communities in particular, and this makes these ideas easier to understand. For example, the competitive urge that motivates humans to war (and to less destructive forms of strife in the business or sports worlds) may be linked to the larger phenomenon of biological competition. Indeed, much of the driving force behind the development of human societies, as it turns out, has been biological in nature.

HOW IT WORKS

The Biosphere, Ecosystems, and Ecology

An ecosystem is a community of interdependent organisms along with the inorganic components of their environment—air, water, and the mineral content of the soil—and a biome is an ecosystem, such as a tundra, that extends over a large area. All living organisms are part of a larger system of life-forms, which likewise interact with large systems of inorganic materials in the operation of a still larger system called *Earth.* (The concepts of ecosystem, biosphere, and biome are discussed, respectively, in Ecosystems and Ecology, The Biosphere, and Biomes.)

Note the importance of the distinctions between living and nonliving and organic and inorganic. Although in popular terms, organic means anything that is living as well as anything that was once living, along with their parts and products (bones, leaves, wood, sap, blood, urine, and so on), in fact, the scientific meaning of the word is both much broader and more targeted. A substance is organic if it contains carbon and hydrogen, and thus organic materials also include such items as plastics that have never been living.

The study of the relationship between living things and their environment, pioneered by the German zoologist Ernst Haeckel (1834–1919) and others, is called ecology. Though the world scientific community was initially slow to accept ecology as a subject of study, the discipline has gained increasing respect since the mid–twentieth century. This change is due to growing acceptance for the idea that all of life is interconnected and that the living world is tied to the nonliving, or inorganic, world. On the other hand, there is also the gathering awareness that certain aspects of industrial civilization may have a negative impact on the environment, an awareness that has spurred further interest in the study of ecology.

Introduction to Biological Communities

The term biological community refers to all the living components in an ecosystem. A slightly different concept is encompassed in the word biota, which refers to all flora and fauna, or plant and animal life, in a particular region.

For the biological community to survive and thrive, a balance must be maintained between consumption and production of resources. Nature provides for that balance in numerous ways, but beginning in the late twentieth century students of ecology in the industrialized world have become more and more concerned with the possible negative impact their own societies exert on Earth's biological communities and ecosystems.

It should be noted, however, that nature itself sometimes replaces biological communities in a process called succession. This process involves the progressive replacement of earlier biological communities with others over time. Coupled with succession is the idea of climax, a theoretical notion intended to describe a biological community that has reached a stable point as a result of ongoing succession. (See Succession and Climax for more about these subjects.)

NICHE. Whereas climax and succession apply to broad biological communities, a niche refers to the role a particular organism or species plays within that community. Though the concept of niche is abstract, it is unquestionable that each organism plays a vital role and that the totality of the biological community (and, indeed, the ecosystem) would suffer stress if a large enough group of organisms were removed from it. Furthermore, given the apparent interrelatedness of all components in a biological community, every species must have a niche—even human beings.

An interesting idea, and one that is somewhat similar to a niche, is that of an indicator species. This is a plant or animal that, by its presence, abundance, or chemical composition, demonstrates a particular aspect of the character or quality of the environment. Indicator species, for instance, can be plants that accumulate large concentrations of metals in their tissues, thus indicating a preponderance of metals in the soil. This metal, in turn, could indicate the presence of valuable deposits nearby, or it could serve as a sign that the soil is being contaminated. (See Food Webs for more about indicator species.)

Another concept closely tied to the concept of niche is that of symbiosis. The latter refers to a biological relationship in which (usually) two species live in close proximity to one another and interact regularly in such a way as to benefit one or both of the organisms. Symbiosis may exist between two or more individuals of the same species, as well as between two or more individuals representing two different species. The three principal varieties of symbiosis are mutualism, in which both participants benefit; commensalism, in which only one participant benefits, but at no expense to the other participant; and parasitism, in which one participant benefits at the expense of the other. These subjects are covered in much greater depth within the essays on Symbiosis and Parasites and Parasitology.

Evaluating Biological Communities

A few billion years ago, Earth's oceans and lands were populated with just a few varieties of single-cell organisms, but over time increasing differentiation of species led to the development of the much more complex ecosystems we know now. Such differentiation is essential, since the life forms in a particular region must adapt to that biome, whether it be forest or grassland, desert or aquatic environments, mountain setting or jungle.

Diversity is a measure of the number of different species within a biological community, while complexity is the number of niches within it. Put another way, the complexity of a community is the number of species that *could* exist in it. Abundance is the measure of populations within individual species; thus, if a biological community has large numbers of individuals, even if it is not diverse in species, it is still said to be abundant.

During its brief summer growing season, the arctic tundra has vast numbers of insects, migratory birds, and mammals, and thus its abundance is high, whereas its diversity is low. On the other hand, a rain forest might have several hundred or even a thousand different tree species, and an even larger number of insect species, in only a few hectares, but there may be only a few individuals representing each of those species in that area. Thus, the forest could have extremely high diversity but low abundance of any particular species. Needless to say, the rain forest is likely to have a much greater complexity than the tundra, meaning that it is theoretically likely to contain far more species.

Another way to evaluate ecosystems is in terms of productivity. Productivity refers to the amount of biomass—potentially burnable energy—produced by green plants as they capture sunlight and use its energy to create new organic compounds that can be consumed by local ani-

mal life. Once again, a forest, and particularly a rain forest, has a very high level of productivity, whereas a desert or tundra ecosystem does not.

FOOD WEBS. Food web (in contrast to the more popular, but less correct term, food chain) is the designation preferred by scientists to describe the means by which energy is transferred through a biological community. Within the food web are various stages, called trophic levels, that identify the position of various organisms in relation to the organisms they consume and the organisms that consume them.

Green plants that depend for their nourishment on photosynthesis, or the biological conversion of electromagnetic energy from the Sun into chemical energy, are primary producers. Herbivores, or plant-eating creatures, are primary consumers, whereas the animals that eat herbivores (whether carnivores or omnivores) are secondary consumers. The largest carnivores and herbivores are usually not prey for any other creatures, but when they die, they, too, will be consumed by detritivores, or scavengers, as well as decomposers, such as bacteria and fungi.

The second law of thermodynamics, one of several laws governing energy and the systems in which that energy is applied, holds that in each energy transfer some energy is lost. In the case of food webs, this means that much of the energy in each trophic level is unavailable to organisms at the next level. This, in turn, means that each successive trophic level generally has far fewer members than the prey on which they feed. While there might be thousands of primary producers in a particular community, there might be only a few top predators, including humans. (See Food Webs for more on these subjects.)

REAL-LIFE APPLICATIONS

Competition

The word competition typically brings to mind images of a basketball court or football field, on one hand, or a Wall Street trading floor or boardroom, on the other. In biological terms, however, competition is the interaction among organisms of the same or different species vying for a common resource that appears in a limited supply relative to the demand. Put another way, this means that the capability of the environment to supply resources is smaller than the potential biological requirement for those resources.

Scarcity of resources relative to the need for them is one of the governing facts of human life, reflected in such common expressions as "There is no such thing as a free lunch." In fact, humans have spent most of their history in a modified form of biological competition, war. Furthermore, it may well be that our modern predilection for sports or business competition is simply a matter of transforming biological competition into a more refined form. In any case, competition prevails throughout the world of living things.

INTRASPECIFIC AND INTERSPECIFIC COMPETITION. For example, plants often compete for access to a limited supply of nutrients, water, sunlight, and space. Intraspecific competition occurs when individuals of the same species vie for access to essential resources (later we look at intraspecific competition between humans), or for mating partners, whereas interspecific competition takes place between different species.

Individuals of the same species have virtually identical resource requirements: for example, all humans need food, water, air, and some protection from the natural elements. For this reason, whenever populations of a species are crowded together, intraspecific competition is intense. This also has been illustrated by experiments involving laboratory mice, which become increasingly brutal to one another when confronted with severely diminished resources. When intraspecific competition occurs in dense populations, the result is a process known as self-thinning, characterized by the mortality (death) of those individuals less capable of surviving coupled with the survival of individuals that are more competitive. If this sounds like the "survival of the fittest," an idea associated with evolution that became the justification for a number of nefarious social movements and activities (see Evolution), it is no accident.

Ideas related to intraspecific competition influenced the English naturalist Charles Darwin (1809–1882) in developing his theory of evolution by means of natural selection. Intraspecific competition is an important regulator of population size and can make the species as a whole more fit by ensuring that only the hardiest individuals survive. Likewise, interspecific competition, or competition between species, plays a



A biome is an ecosystem, such as a tundra, that extends over a large area. In the arctic tundra, competition is low, but creatures like this arctic fox face such powerful environmental stresses from the local climate that competition is not the most significant factor limiting populations. *(Photo Researchers. Reproduced by permission.)*

strong role in shaping ecological communities. Furthermore, competition between species is also an agent of natural selection.

COMPETITIVE RELEASE. Environmental changes that affect a biological community may change the competitive relationships within it, leading to interesting results. During the early 1950s, a fungal pathogen (a disease-carrying parasite in the form of a fungus) known as chestnut blight, or *Endothia parasitica,* ended the dominance of the American chestnut in the eastern United States. Up to that time, the American chestnut (*Castanea dentata*) had been the leading species in the canopy, or uppermost layer, of the deciduous (prone to seasonal shedding of leaves) forests in the region. Thanks to the chestnut blight, it was as though the winner had been disqualified from a race, meaning that all the runners-up changed their standings.

By being relieved of the stresses associated with competition, other trees were allowed to become more successful and dominant in their habitat. They took advantage of this change to fill in the canopy gaps left by the demise of mature chestnut trees. In the same way, if a wildfire, storm, or other stress disturbs a mature forest, plants that previously have been suppressed by the higher-canopy trees find themselves with much greater access to such resources as light, moisture, and nutrients. As a result, they thrive.

Given the distasteful aspects of biological competition, such as the destruction of the "weak" in favor of the "strong" (actually, less adapted and more adapted are much more accurate terms in this context), one might wish for a situation in which no competition exists. Indeed, there are such situations in nature, but they are far from pleasant. In such biomes as the arctic tundra, for instance, competition is low, but this is not because all nature lives in happiness and harmony; instead, organisms face such powerful environmental stresses from the local climate that competition is not the most significant factor limiting populations.

THE TUNDRA BIOLOGICAL COMMUNITY. Creatures on the tundra face little stress from competition, but a great deal of stress in the form of very short growing seasons, thin soil, limited ground cover, low average temperatures and rainfall, high winds, and so on. If the density of individual plants of the tundra is decreased experimentally by thinning, the resid-

ual plants do not thrive as a result, as they might in a less harsh climate. In the case of the tundra, it is not competition that constrains their productivity, and therefore the reduction of potential competition does little to improve conditions for the organisms that survive.

It is interesting to observe what happens in a tundra environment if the intensity of environmental stress is artificially and experimentally alleviated by enclosing an area under a greenhouse and by fertilizing it with nutrients. Such experiments have been performed, and the results are fascinating: under these more favorable environmental conditions, competition actually increases, resulting in a biological community not unlike that of a more hospitable biome.

Biological Communities and Civilizations

In his best-seller *Guns, Germs, and Steel: The Fate of Human Societies,* ethnobotanist Jared M. Diamond showed that local biological communities are among the leading determinants of the success or failure of human civilizations. The book had its beginnings, he wrote, during his many years of work with the native peoples of New Guinea. One day, a young man put a simple question to him: why do the societies of the West enjoy an abundance of material wealth and comforts, while those of New Guinea have so little?

The question may have been simple, but the answer was not obvious. As a scientist, Diamond refused to give an answer informed by the politics of the Left or Right, which might have blamed the problem, respectively, on western exploitation or on the failures of the New Guineans themselves. Instead, he approached it as a question of environment, and the result was his thought-provoking analysis, contained in *Guns, Germs, and Steel.*

Favorable and unfavorable ecosystems. As Diamond showed, the places where agriculture was born were precisely those blessed with favorable climate, soil, and indigenous plant and animal life. Of course, it is no accident that civilization was born in the societies where agriculture first developed. Before a civilization can evolve, a society must become settled, and for that to happen, it must have agriculture.

Agriculture came into existence in four places during a period from about 8000 to 6000 B.C. In roughly chronological order, these locations were Mesopotamia, Egypt, India, and China. All were destined to emerge as civilizations, complete with written language, cities, and organized governments, between about 3000 and 2000 B.C.

In the New World, by contrast, agriculture appeared much later and in a much smaller way. The same was true of Africa and the Pacific Islands. In seeking to find the reasons why this happened, Diamond noted a number of factors, including geography. The agricultural areas of the Old World were stretched across a wide area at similar latitudes. This meant that the climates were not significantly different and would support agricultural exchanges, such as the spread of wheat and other crops from one region or ecosystem to another. By contrast, the landmasses of the New World or Africa have a much greater north-to-south distance than they do east to west, resulting in great differences of climate.

Diversity of species. Today such places as the American Midwest support abundant agriculture, and one might wonder why that was not the case in the centuries before Europeans arrived. The reason is simple but subtle, and it has nothing to do, as many Europeans and their descendants believed, with the cultural "superiority" of Europeans over Native Americans. The fact is that the native North American biological communities were far less diverse than their counterparts in the Old World. Peoples of the New World successfully domesticated corn and potatoes, because those were available to them. But they could not domesticate emmer wheat, the variety used for making bread, when they had no access to that species (it originated in Mesopotamia and spread throughout the Old World).

The New World also possessed few animals that could be domesticated either for food or for labor. Every single plant or animal that is a part of human life today had to be domesticated—adapted in such a way that it becomes useful and advantageous for humans—and the range of species capable of domestication is far from limitless. In fact, it is safe to say that all major species capable of being domesticated have been, thousands of years ago. The list of animals that can be domesticated is a short one, much shorter than the list of animals that can be tamed. A bear, for instance, can be captured, or raised from birth in captivity, but it is unlikely that humans would ever be able to breed bears in such a way that



A smallpox victim shows the characteristic lesions on his limbs. Europeans' advantage over the Native Americans derived from the ecological complexity of their biological communities, even down to the world of microorganisms. The native peoples of the New World had no natural resistance to smallpox or a host of other diseases. *(© Corbis. Reproduced by permission.)*

their wild instincts all but disappeared and they became reliable, useful companions.

The animals that helped make possible the development of farms, villages, and ultimately empires in the Old World—cows and oxen, horses and donkeys, sheep and so on—were absent from the New World. (Actually, horses had once existed in the Americas, but they had been destroyed through overhunting, as discussed in the context of mass extinction within the Paleontology essay.) Many Indian tribes domesticated some types of birds and other creatures for food, but the only animal ever adapted for labor—by the most developed civilization of the pre-Columbian Americas, the Inca—was the llama, which is too small to carry heavy loads.

GREATER EXPOSURE TO MICROORGANISMS. The Europeans' advantage over the Native Americans derived ultimately from the ecological complexity of their biological communities compared with those of the Native Americans. This was also true of the "biological communities" they could not see, and of which people were unaware in 1500: the world of microorganisms, or the "germs" in the title of Diamond's book.

The native peoples of the New World had no natural resistance to smallpox or a host of other diseases, including measles, chicken pox, influenza, typhoid fever, and the bubonic plague. As with many plants and animals of the Old World, they simply had no exposure to these microorganisms. In the Old World, however, close contact with farm animals exposed humans to diseases, as did close contact with other people in crowded, filthy cities. This exposure, of course, killed off large numbers in such plagues as the Black Death (1347–1351), but those who survived tended to be much stronger and possessed vastly greater immunities. Therefore, the vast majority of Native American deaths that followed the European invasion were not a result of warfare, enslavement, or massacre of villages (though all of these occurred as well), but of infection. (See Infection and Infectious Diseases for more on these subjects.)

CANNIBALISM. Even the practice of cannibalism in such remote locations as the New Guinea highlands is, according to Diamond, a consequence of a relatively limited biological community. In the past, westerners assumed that only very "primitive" societies engaged in cannibalism. However, events have shown that, when faced with starvation, even people from European and European-influenced civilizations may consume human flesh in order to survive.

For instance, in 1846 members of the Donner party, making the journey west across North America, resorted to eating the bodies of those who had died in the perilous crossing. Much the same happened in the 1970s, when a plane carrying Uruguayan athletes crashed in the Andes, and the survivors lived off the flesh of those who had died. Though their upbringing and cultural norms may have told them that cannibalism was immoral or at the very least disgusting, their bodies told them that if they did not consume the only available food, they would die.

Whereas these circumstances were unusual and temporary, peoples in some parts of the world have been faced with a situation in which the only sources of protein provided within the biological community are ones whose consump-

KEY TERMS

ABUNDANCE: A measure of the degree to which an ecosystem possesses large numbers of particular species. An abundant ecosystem may or may not have a wide array of different species. Compare with *complexity.*

BIOENERGY: Energy derived from biological sources that are used directly as fuel (as opposed to food, which becomes fuel). Examples of bioenergy include wood or manure that can be burned. Usually, petrochemicals, such as petroleum or natural gas, though they are derived from the bodies of dead organisms, are treated separately from forms of bioenergy.

BIOLOGICAL COMMUNITY: The living components of an ecosystem.

BIOMAGNIFICATION: The increase in bioaccumulated contamination at higher levels of the food web. Biomagnification results from the fact that larger organisms consume larger quantities of food—and, hence, in the case of polluted materials, more toxins.

BIOMASS: Materials that are burned or processed to produce bioenergy.

BIOME: A large ecosystem, characterized by its dominant life-forms.

BIOSPHERE: A combination of all living things on Earth—plants, animals, birds, marine life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

BIOTA: A combination of all flora and fauna (plant and animal life, respectively) in a region.

CANOPY: The upper portion or layer of the trees in a forest. A forest with a closed canopy is one so dense with vegetation that the sky is not visible from the ground.

CARNIVORE: A meat-eating organism, or an organism that eats *only* meat (as distinguished from an omnivore).

CLIMAX: A theoretical notion intended to describe a biological community that has reached a stable point as a result of ongoing succession.

COMPLEXITY: The range of ecological niches within a biological community. The degree of complexity is the number of different species that theoretically *could* exist in a given biota, as opposed to its diversity, or actual range of existing species.

DECOMPOSERS: Organisms that obtain their energy from the chemical breakdown of dead organisms as well as from animal and plant waste products. The principal forms of decomposer are bacteria and fungi.

DECOMPOSITION REACTION: A chemical reaction in which a compound is broken down into simpler compounds, or into its constituent elements. In the biosphere, this often is achieved through the help of detritivores and decomposers.

DETRITIVORES: Organisms that feed on waste matter, breaking organic material down into inorganic substances that then can become available to the biosphere in the form of nutrients for plants. Their function is similar to that of decomposers; however, unlike decomposers—which tend to be bacteria or fungi—detritivores are

KEY TERMS CONTINUED

relatively complex organisms, such as earthworms or maggots.

DIVERSITY: A measure of the number of different species within a biological community.

ECOLOGY: The study of the relationships between organisms and their environments.

ECOSYSTEM: A community of interdependent organisms along with the inorganic components of their environment.

ENERGY TRANSFER: The flow of energy between organisms in a food web.

HERBIVORE: A plant-eating organism.

INDICATOR SPECIES: A plant or animal that, by its presence, abundance, or chemical composition, demonstrates a particular aspect of the character or quality of the environment.

NATURAL SELECTION: The process whereby some organisms thrive and others perish, depending on their degree of adaptation to a particular environment.

NICHE: A term referring to the role that a particular organism plays within its biological community.

OMNIVORE: An organism that eats both plants and other animals.

PATHOGEN: A disease-carrying parasite, usually a microorganism.

PHOTOSYNTHESIS: The biological conversion of light energy (that is, electromagnetic energy) from the Sun to chemical energy in plants.

PRIMARY PRODUCERS: Green plants that depend on photosynthesis for their nourishment.

PRODUCTIVITY: The amount of biomass produced by green plants in a given biome.

SUCCESSION: The progressive replacement of earlier biological communities with others over time.

TROPHIC LEVELS: Various stages within a food web. For instance, plants are on one trophic level, herbivores on another, and so on.

tion seems repugnant from the western viewpoint. Discussing the New Guinea highlands, Diamond noted that the area is virtually bereft of protein sources in the form of large, nonhuman mammals. Nor is bird life sufficient to support the local populace, and marine food sources are far away. For this reason, natives are prone not only to cannibalism but also to another culinary practice that most westerners find appalling: eating bugs, worms, grubs, caterpillars, and other creepy-crawly creatures.

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SUCCESSION AND CLIMAX

CONCEPT

Eventually almost everyone has the experience of watching an old neighborhood change. Sometimes we perceive that change for the better, sometimes for the worse, and the perception can have more to do with our individual desires or needs than it does with any qualities inherent in the change itself. For instance, one person might regard a new convenience store and gas station as an eyesore, while another might welcome it as a handy place to buy coffee, gasoline, or other items. Likewise, biological "neighborhoods" change, as when a complete or nearly complete community of living things replaces another. Once again, changes are not necessarily good or bad in any fundamental sense; rather, one community that happens to be better adapted to the changed environment replaces another. Sometimes a stress to the ecosystem brings about a change, such that life-forms that once were adapted to the local environment are no longer. Still, there appears to be a point when a community achieves near perfect adaptation to its environment, a stage in the levels of succession known as *climax*. This is the situation of old-growth forests, a fact that explains much about environmentalist opposition to logging in such situations.

HOW IT WORKS

Biogeography

Elsewhere in this book, there is considerable material about ecosystems, or communities of interdependent organisms along with the inorganic components of their environment, as well as about biological communities, or the living components of an ecosystem. There are also discussions of biomes, or large ecosystems, and food webs, or the means by which energy transfer takes place across a biological community. Related to many of these ideas, as well as to succession and climax, is the realm of biogeography, or the study of the geographic distribution of plants and animals, both today and over the course of biological history.

Biogeography, which emerged in the nineteenth century amid efforts to explore and map the planet fully, draws on many fields. Among the areas that overlap with this interdisciplinary realm of study are the biological sciences of botany and zoology, the combined biological and earth sciences of oceanography and paleontology, as well as the earth sciences of geology and climatology. Not only do these disciplines contribute ideas to the growing field of biogeography, but they also make use of ideas developed by biogeographers. Biogeography is concerned with questions regarding local and regional variations in kinds and numbers of species and individuals. Among the issues addressed by biogeography are the reasons why particular species exist in particular areas, the physical and biotic (life-related) factors that influence the geographic range over which a species proliferates, changes in distribution of species over time, and so on.

Species interact by three basic means: competition for resources, such as space, sunlight, water, or food (see Biological Communities for more about competition); predation, or preying, upon one another (see Food Webs); and symbiosis. An example of the latter form of interaction, discussed elsewhere (see Symbiosis), occurs when an insect pollinates a plant while the plant provides the insect with nourishment, for instance, in the form of nectar. These interac-

tions can and do affect the geographic distribution of species, and the presence or absence of a particular life-form may serve as a powerful control on the range of another organism.

Other significant concepts in the realm of biogeography are dispersal (the spread of a species from one region to another), and barriers (environmental factors that act to block dispersal). A species may extend its geographic range by gradually colonizing, or taking over, adjacent areas, or it may cross a barrier (for instance, a mountain range, an ocean, or a desert) and colonize the lands beyond. Later, we briefly examine the case of a bird that managed to do both.

Succession

Succession is the progressive replacement of earlier biological communities with others over time. It entails a process of ecological change, whereby new biotic communities replace old ones, culminating in a stable ecological system known as a climax community. In a climax community, climate, soil, and the characteristics of the local biota (the sum of all plants and animals) are all suited to one another.

At the beginning of the succession process, a preexisting ecosystem undergoes some sort of disturbance—for example, a forest fire. This is followed by recovery, succession, and (assuming there are no further significant disturbances) climax. If the environment has not been modified previously by biological processes, meaning that succession takes place on a bare substrate, such as a sand dune or a dry riverbed, it is known as primary succession. Primary succession also occurs when a previous biological community has been obliterated. Secondary succession takes place on a substrate that has been home to other lifeforms and usually in the wake of disturbances that have not been so sweeping that they prevented the local vegetation from regenerating.

THE FACILITATION MODEL. Whether the conditions are those of primary or secondary succession, the outcome of the preceding disturbance is such that resources are now widely available, but there is little competition for them. One way of describing this situation is through what is known as the facilitation model, which identifies "pioneer species" as those lifeforms most capable of establishing a presence on the site of the disturbance.

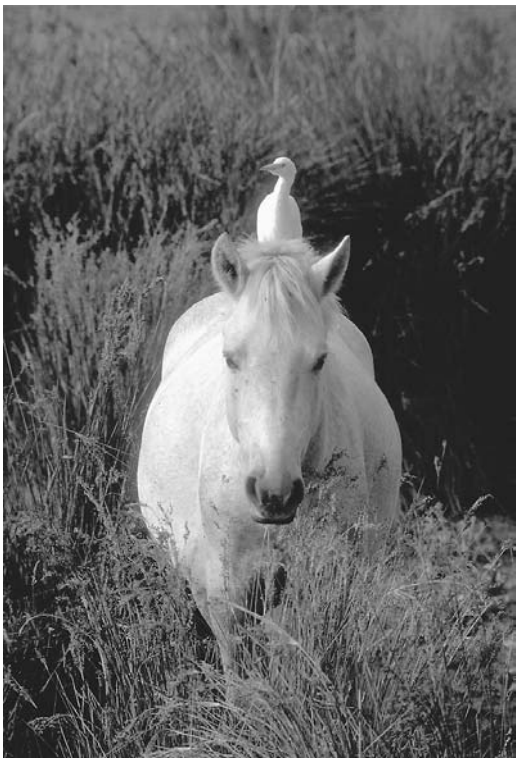
Pioneers modify a site by their presence, for instance, by regenerating the soil with organic material, thus making the area more attractive for invasion by other species. Eventually, new species move in, edging out the pioneers as they do so. This process may repeat itself several times, until the ecosystem reaches the climax stage, which we examine in greater depth a bit later in this essay. At the climax stage, there are few biological "openings" for further change, and change is only very slight and slow—at least until another disturbance arises and starts the process over again.

THE TOLERANCE MODEL. The tolerance model is another possible mechanism of succession. According to this concept, all species involved in succession are equally capable of establishing themselves on a recently disturbed site, but those capable of attaining a large population size quickly are most likely to become dominant. Unlike the facilitation model, the tolerance model does not depict earlier inhabitants as preparing the site biologically for new invader species; rather, this model is more akin to natural selection, discussed elsewhere (see Evolution).

According to the tolerance model, some species will prove themselves more tolerant of biological stresses that occur within the environment as succession proceeds. Among these stresses is competition, and those species less tolerant of competition may succeed earlier on, when there is little competition for resources. Later in the succession process, however, such species will be eliminated in favor of others more capable of competing.

THE INHIBITION MODEL. Yet another model of succession is the inhibition model, which, like the tolerance model, starts with the premise of an open situation at the outset: in other words, all species have equal opportunity to establish populations after a disturbance. In the inhibition model, however, some of the early species actually make the site less suitable for the development of other species. An example of this is when plants secrete toxins in the soil, thus inhibiting the establishment and growth of other species. Nevertheless, in time the inhibitory species die, thus creating opportunities that can be exploited by later successional species.

There is evidence to support all three models—facilitation, tolerance, and inhibition—but just as each has a great deal of basis in fact, none of the three fully depicts the dynamics of a suc-



Cattle egret and wild horse in southern France. During the nineteenth century, the Old World cattle egret managed to cross the Atlantic and found a breeding colony in Brazil. Since then, it has expanded the range of its habitats, so that colonies can be found as far north and east as Ontario and as far south and west as southern Chile. *(© Hellio/Van Ingen. Photo Researchers. Reproduced by permission.)*

cessional environment. Put another way, each is fully right in one particular instance, but none are correct in all circumstances. Facilitation seems to work best for describing primary succession, whereas the more intense, vigorous environment of secondary succession is best pictured by tolerance or inhibition models. All of this shows that succession patterns tend to be idiosyncratic, owing to the many variables that determine their character.

Climax

When a biological community reaches a position of stability and is in equilibrium with environmental conditions, it is said to have reached a state of climax. Often such communities are described as *old growth,* and in these situations change takes place slowly. Dominant species in a climax community are those that are highly tolerant of the biological stresses that come with competition. And well they might be, since by the climax stage, resources have been allocated almost completely among the dominant life-forms.

Despite its slow rate of change, the climax community is not a perfectly static or unchanging one, because microsuccession (succession on the scale of a single tree, or a stand of trees) is always taking place. In fact, frequent enough events of disturbance within small sections of the biological community may prevent climax from even occurring. Once the biota does achieve a state of equilibrium with the environment, however, it is likely that change will slow down considerably, bringing an end to the stages of succession. Climax remains a somewhat theoretical notion, and in practice it may be difficult to identify a climax community.

Real-Life Applications

Colonization and Island Biogeography

Earlier, in the context of biogeography, there was a reference to animals "colonizing." This may sound like the behavior of humans only, but other animals are also capable of colonizing. Nor are humans the only creatures that crossed the Atlantic Ocean from the Old World to colonize parts of the New World. During the nineteenth century, an Old World bird species known as the cattle egret managed to cross the Atlantic, perhaps driven by a storm, and founded a breeding colony in Brazil. Since then, it has expanded the range of its habitats, so that cattle egret colonies can be found as far north and east as Ontario and as far south and west as southern Chile.

The biogeography of isolated biomes. Colonization is one example of the phenomena studied within the realm of biogeography. Other examples involve islands, and, indeed, island biogeography is a significant subdiscipline. The central idea of island biogeography, a discipline developed in 1967 by American biologists R. H. MacArthur (1930–1972) and Edward O. Wilson (1929–), is that for any landmass a certain number of species can coexist in a state of equilibrium. The larger the size of the landmass, the larger the number of species. Thus, reasonably enough, a large island should have a great number of species, whereas a small one should support only a few species.

These principles have helped in the study of other "island" ecosystems that are not necessarily on islands but rather in or on isolated lakes, mountain ranges surrounded by deserts, and patches of forest left behind by clear-cut logging. As a result of such investigations, loggers in the forests of the Pacific Northwest or the Amazon valley have been encouraged to leave behind larger stands of trees in closer proximity to one another.

This makes possible the survival of species at higher trophic levels (positions on the food web) and of those with very specialized requirements as to food or habitat. Examples of the latter species include Amazonian monkeys and the northern spotted owl, which we discuss later. Because studies in island biogeography have made land-use planners more aware of the barriers posed by clear-cut foresting, it has become common practice to establish "forest corridors." These long, thin lines of trees connecting sections of forest ensure that one section will not be isolated completely from another.

Succession in Action

In discussing succession earlier, it was noted that a disturbance usually sets the succession process in motion. Examples of such disturbances can include seismic events (earthquakes, tidal waves, or volcanic eruptions) and weather events (hurricanes or tornadoes). Across larger geologic timescales, the movement of glaciers or even of plates in Earth's crust (see Paleontology for more about plate tectonics and its effect on environments) can set succession processes in motion.

There are also causes directly within the biosphere, or the realm of all life, that can bring about disturbances. Among them are wildfires as well as sudden infestations of insects that act to defoliate, or remove the leaf cover from, a mature forest. Quite a few disturbances can result from activities on the part of the biosphere's most complex species: *Homo sapiens.* Humans can cause ecological disturbances by plowing up ground, by harvesting trees from forests, by bulldozing land for construction purposes—even by causing explosions on a military reservation or battlefield.

Disturbances can take place on a grand scale or a small scale. It is theoretically possible for disturbances—even man-made ones—to wipe out forests as large as the Ardennes in northwestern Europe or the Amazon rain forest in South America. Fortunately, neither shelling in the Ardennes during the world wars nor logging in the Amazon valley in the late twentieth century managed to destroy those biomes, but it is quite conceivable that they could have. On the other hand, a disturbance can affect an individual lifeform, as when lightning strikes and kills a mature tree in a forest, creating a gap that will be filled through the growth of another tree—an example of microsuccession.

Forms of succession. Once succession begins, it can take one of several courses. It may lead to the restoration of the ecosystem in a form similar to that which it took before the disturbance. Or, depending on environmental circumstances, a very different ecosystem may develop. For example, suppose that a forest fire has wiped out a biological community and secondary succession has begun. It is conceivable that this succession process will restore the forest to something approaching its former state. On the other hand, the wildfire itself may well have been a signal of a climate change, in this case, to a drier, warmer environment. In this instance, succession may bring about a community quite different from that which preceded the disturbance.

The "disturbance" itself actually may be the alleviation of a long-term environmental stress that has plagued the community. Suppose that a biological community has suffered from a local source of pollution, for instance, from a factory dumping toxins into the water supply. Suppose, too, that pressure from state or federal authorities finally forces a cleanup. How does this affect the biotic environment? In all likelihood, species that are sensitive to pollution (i.e., ones that normally could not survive in polluted conditions) would invade the area.

Removal of an environmental stress may not always be a matter of pollution and cleanup. For instance, a herd of cattle may be overgrazing a pasture, thus holding back the growth of plant species in the area. Imagine, then, that the cattle are moved elsewhere; as a result, new plant species will proliferate in the area, and, in all likelihood, the biological diversity of that particular ecosystem will increase.

Primary Succession

As we noted earlier, primary succession occurs in an environment where there has never been a significant biological community or in the wake of



Glacier Bay, Alaska, is an example of an ecosystem that experienced primary succession in the wake of deglaciation; as the glaciers melted, various plants moved in, each taking its turn as dominant species. The habitat now has reached maturity, and access to resources is allocated as fully as it can be among the dominant species. *(© Pat O'Hara/Corbis. Reproduced by permission.)*

disturbances that have been intense enough to wipe out all traces of a biological community. An example of primary succession in an area that has not possessed a biological community would be an abandoned paved parking lot. Eventually, the asphalt would give way to plant life, and given



Israeli farmers try to ward off a swarm of locusts. Defoliation brought about by insects is one example of the type of disturbance that may serve as a precursor to secondary succession. *(© Hulton-Deutsch Collection/Corbis. Reproduced by permission.)*

enough time, a wide-ranging biological community might develop around it.

These statements should be qualified in two ways, however. When it is said that an area has not maintained a significant biological community, this refers only to the recent or relatively recent past. In the case of the parking lot area, there probably have been countless biological communities in that spot over the ages, each replaced by the other in a process of primary succession. Also, by *significant biological community* we mean a biological community that exists *above* ground; even in the instance of the parking lot, there would be an extensive biological community underground. (See The Biosphere for more about life in the soil.)

Glacier Bay. Glacier Bay, in southern Alaska, is an example of an ecosystem that experienced primary succession in the wake of deglaciation, or the melting of a glacier. The glaciers there have been melting for at least the past few hundred years, and as this melting began to occur, plants moved in. The first were mosses and lichens, flowering plants such as the river-beauty (*Epilobium latifolium*), and the mountain avens (*Dryas octopetala*), noted for their ability to "fix" or transform nitrogen into forms usable by the soil. (See The Biosphere for more about nitrogen fixing and biogeochemical cycles.)

These were the pioneer species, and over time they were replaced by larger plants, such as a short version of the willow. Later, taller shrubs, such as the alder (also a nitrogen-fixing species), dominated the area for about half a century. In time, Sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga heterophylla*), and mountain hemlock (*T. mertensiana*) each had its turn as dominant plant species. With the last group, Glacier Bay reached climax, meaning that the dominant species are not those most tolerant of stresses associated with competition. The habitat thus has reached maturity, and access to resources is allocated as fully as it can be among the dominant species. Accompanying these changes have been changes in nonliving parts of the ecosystem as well, including the soil and its acidity.

Secondary Succession

When a disturbance has not been so intense or sweeping as to destroy all life within an ecosystem, regeneration may occur, bringing about secondary succession. But regeneration of existing species is not the only mechanism that makes secondary succession possible; invasions by new

plant species typically augment the succession process. While much else changes in the environment of a secondary succession, the quality of the soil itself remains constant, as do other characteristics, such as climate.

Because it is rare for a disturbance to be powerful enough to obliterate all preexisting lifeforms, secondary succession is much more common than primary succession. Examples of the type of disturbance that may serve as a precursor to secondary succession are windstorms, wildfires, and defoliation brought about by insects—provided, of course, that the destruction caused by these phenomena is less than total. The same is true of most disturbances associated with human activities, such as the abandonment of agricultural lands and the harvesting of forests by cutting down trees for lumber or pulp.

In a forest of mixed species in the eastern United States, the dominant trees are a mixture of angiosperms and coniferous species (respectively, plants that reproduce by producing flowers and those that reproduce by producing cones bearing seeds), and there are plant species capable or surviving under the canopy, or "roof," provided by these trees. Suppose that the forest has been clear-cut. This means that most or all of the large trees have been removed, but the entire biological community has not been wiped out, since loggers typically would not bother to cut down smaller plants that are not in their way.

As soon as the clear-cutting is over, regeneration begins. One form that this takes is the formation of new sprouts from the stumps of the old angiosperms. These sprouts are likely to grow rapidly and then experience a process of self-thinning, in which only the hardiest shoots survive. Within half a century, a given tree will have only one to three mature stems growing from its stump.

At the same time, other species regenerate seemingly from nowhere, though actually they are growing from a "seed bank" buried in the forest floor, where trees have dropped countless seeds over the generations. Species such as the pin cherry (*Prunus pennsylvanica*) and red raspberry (*Rubus strigosus*) are particularly adept at regeneration in this form. Therefore, these species are likely to feature prominently in the forest during the first several decades of secondary succession.

On the other hand, some tree species simply do not survive clear-cutting, or at least not in large numbers; if they are to obtain a stake in the secondary succession, they must do so by a process of re-invasion. Such often happens in the case of coniferous trees. Other species may also invade when they have not previously been a part of the habitat, yet they enter now because the temporary conditions of resource availability and limited competition make the prospect for invasion attractive. A great number of species, from alders and white birch to various species of grasses, fit into this last category.

Plants are not the only organisms involved in secondary succession. In a mature forest of the type described, the dominant bird forms probably include species of warblers, vireos, thrushes, woodpeckers, and flycatchers. When clear-cutting occurs, however, these birds are likely to be replaced by an entirely new avian community—one composed of birds more suited to the immature habitat that follows a disturbance. As time passes, however, and the forest regenerates fully, the bird species of the mature forest re-invade and resume dominance, a process that may well take three to four decades.

Old-Growth Forests

Old-growth forests represent a climax ecosystem—one that has come to the end of its stages of succession. They are dominated by trees of advanced age (hence the name *old-growth*), and the physical structure of these ecosystems is extraordinarily complex. In some places, the forest canopy is dense and layered, whereas in others it has gaps. Tree sizes vary enormously, and the forest is littered with the remains of dead trees.

An old-growth forest, by definition, takes a long time to develop. Not only must it have been free from human disturbance, but it also must have been spared various natural disturbances of the kind that we have mentioned, disturbances that bring about the conditions for succession. Typically, then, most old-growth forests are rain forests in tropical and temperate environments, where they are unlikely to suffer such stresses as drought and wildfire. Among North American old-growth forests are those of the United States Pacific Northwest as well as in adjoining regions of southwestern Canada.

THE SPOTTED OWL. These old-growth forests of North America are home to a bird that became well known in the 1980s and 1990s to environmentalists and their critics: the

KEY TERMS

ABUNDANCE: A measure of the degree to which an ecosystem possesses large numbers of particular species. An abundant ecosystem may or may not have a wide array of different species. Compare with *complexity.*

ANGIOSPERM: A type of plant that produces flowers during sexual reproduction.

BIOGEOGRAPHY: The study of the geographic distribution of plants and animals, both today and over the course of extended periods.

BIOLOGICAL COMMUNITY: The living components of an ecosystem.

BIOME: A large ecosystem, characterized by its dominant life-forms.

BIOSPHERE: A combination of all living things on Earth—plants, animals, birds, marine life, insects, viruses, single-cell organisms, and so on—as well as all formerly living things that have not yet decomposed.

BIOTA: A combination of all flora and fauna (plant and animal life, respectively) in a region.

BIOTIC: Life-related.

CANOPY: The upper portion or layer of the trees in a forest. A forest with a closed canopy is one so dense with vegetation that the sky is not visible from the ground.

CLIMATE: The pattern of weather conditions in a particular region over an extended period. Compare with *weather.*

CLIMAX: A theoretical notion intended to describe a biological community that has reached a stable point as a result of ongoing succession. In such a situation, the community is at equilibrium with environmental conditions, and conditions are stable, such that the biota experiences little change thereafter.

COMPETITION: Interaction between organisms of the same or different species brought about by their need for a common resource that is available in quantities insufficient to meet the biological demand.

COMPLEXITY: The range of ecological niches within a biological community. The degree of complexity is the number of different species that *could* exist, in theory, in a given biota, as opposed to its diversity, or the actual range of existing species.

CONIFER: A type of tree that produces cones bearing seeds.

DIVERSITY: A measure of the number of different species within a biological community.

ECOSYSTEM: A community of interdependent organisms along with the inorganic components of their environment.

FOOD WEB: A term describing the interaction of plants, herbivores, carnivores, omnivores, decomposers, and detritivores in an ecosystem. Each of these organisms consumes nutrients and passes it along to other organisms. Earth scientists typically prefer this name to *food chain,* an everyday term for a similar phenomenon. A food chain is a series of singular organisms in which each plant or animal depends on the organism that precedes it. Food chains rarely exist in nature.

FOREST: In general terms, a forest is simply any ecosystem dominated by tree-

KEY TERMS CONTINUED

size woody plants. Numerous other characteristics and parameters (for example, weather, altitude, and dominant species) further define types of forests, such as tropical rain forests.

MICROSUCCESSION: Succession on a very small scale within a larger ecosystem or biological community. Microsuccession can occur at the level of a stand of trees or even a single tree.

NATURAL SELECTION: The process whereby some organisms thrive and others perish, depending on their degree of adaptation to a particular environment.

NICHE: A term referring to the role that a particular organism plays within its biological community.

OLD-GROWTH: An adjective for a climax community.

SUCCESSION: The progressive replacement of earlier biological communities with others over time. Succession, which can culminate in a climax community (see *climax*), is either primary, which occurs where there is no preexisting biological community (or no such community has survived), or secondary, in which a biological community regenerates in the wake of a disturbance, such as a forest fire.

TROPHIC LEVELS: Various stages within a food web. For instance, plants are on one trophic level, herbivores on another, and so on.

northern spotted owl, or *Strix occidentalis caurina.* A nonmigratory bird, the spotted owl has a breeding pattern such that it requires large tracts of old-growth, moist-to-wet conifer forest as its habitat. These are the spotted owl's environmental requirements, but given the potential economic value of old-growth forests in the region, the situation was bound to generate heated controversy as the needs of the spotted owl clashed with those of local humans.

On the one hand, environmentalists insisted that the spotted owl's existence would be threatened by logging, and, on the other, representatives of the logging industry and the local community maintained that prevention of logging in the old-growth forests would cost jobs and livelihoods. The question was not an easy one, pitting the interests of the environment against those of ordinary human beings. By the early 1990s the federal government had stepped in on the side of the environmentalists, having recognized the spotted owl as a threatened species under the terms of the U.S. Endangered Species Act of 1973. Even so, controversy over the spotted owl—and over the proper role of environmental, economic, and political concerns in such situations—continues.

CONTINUING CONTROVERSY. Another concern raised by the logging of old-growth forests has been the need to preserve dead trees, which provide a habitat for woodpeckers and other varieties of species. This concern, too, has brought about conflict with loggers, who find that dead wood gets in the way of their work. *Dead wood,* after all, is an expression for something or someone that is not performing a useful function (as in, "We're removing all the dead wood from the team"), and to loggers this literal dead wood is nothing more than a nuisance.

Unfortunately, the United States logging industry typically has not pursued a strategy of attempting to manage old-growth forests as a renewable resource, which these forests could be, given enough time. Instead, logging companies—interested in immediate profits and not much else—have tended to treat old-growth forests as though they were more like coal mines, home of a nonrenewable resource. In this "mining" model of tree harvesting, the forest is allowed to experience a process of succession

such that a younger, second-growth forest emerges. Over time, this might become an old-growth forest, but the need to turn a quick profit means that the forest likely will be cut down before that time comes.

The average citizen, who typically has no vested interest in the side of either the loggers or the environmentalists, might well find good and bad on both sides of the issue. Certainly, the image of radical environmentalists chaining themselves to trees is as distasteful as the idea of loggers removing valuable natural resources. There is also a class dimension to the struggle, since a person deeply concerned about environmental issues is probably someone from an economic level above mere survival. This results in another distasteful image: of upper-middle-class and upper-class environmentalists inhibiting the livelihood of working-class loggers.

On the other hand, as we have already suggested, the logging companies themselves are big business and hardly representative of the working class. Largely as a result of pressure from environmentalists, these companies have attempted to develop more environmentally responsible logging schemes under the framework of what is called *new forestry.* These practices involve leaving a forest largely intact and removing only certain trees. Many environmentalists contend, however, that even the new forestry disturbs the essential character of old-growth forests.

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