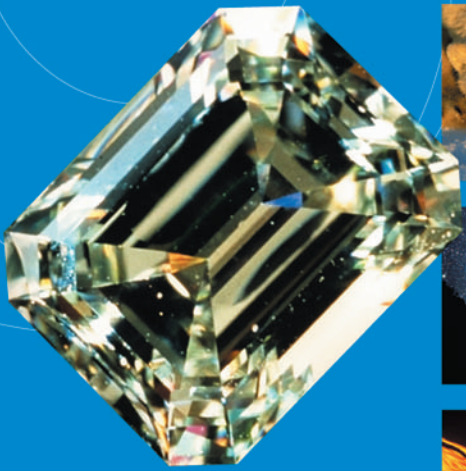
# SCIENCE OF EVERYDAY THINGS

## VOLUME 4: REAL-LIFE EARTH SCIENCE









EDITED BY NEIL SCHLAGER
WRITTEN BY JUDSON KNIGHT

# SCIENCE OF EVERYDAY THINGS

## VOLUME 1: REAL-LIFE CHEMISTRY

EDITED BY NEIL SCHLAGER
WRITTEN BY JUDSON KNIGHT

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

A Schlager Information Group Book
Neil Schlager, Editor
Written by Judson Knight


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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.

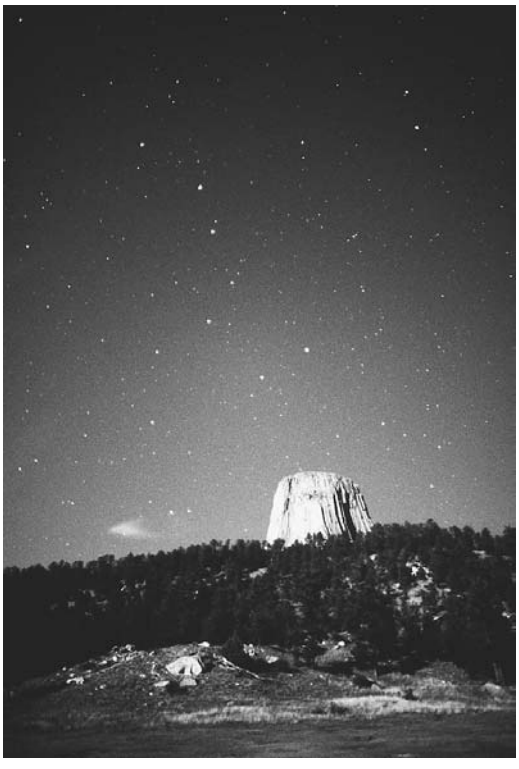
**SIX DAYS?** Actually, 2 Genesis concerns Adam's life before the Fall as well as the creation of Eve from his rib, so the Creation story proper is confined to the first chapter. One of the most famous passages in Western literature, 1 Genesis describes God's creation of the universe in all its particulars, 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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*Sevil Atasoy's Links of Forensic Geology* (Web site). <http://abone.turk.net/atasoy/forensicgeology.html>.

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*What Can I Do with a Degree in Geology?* (Web site). <http://www.hartwick.edu/geology/alumni/careers.html>.

# 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.

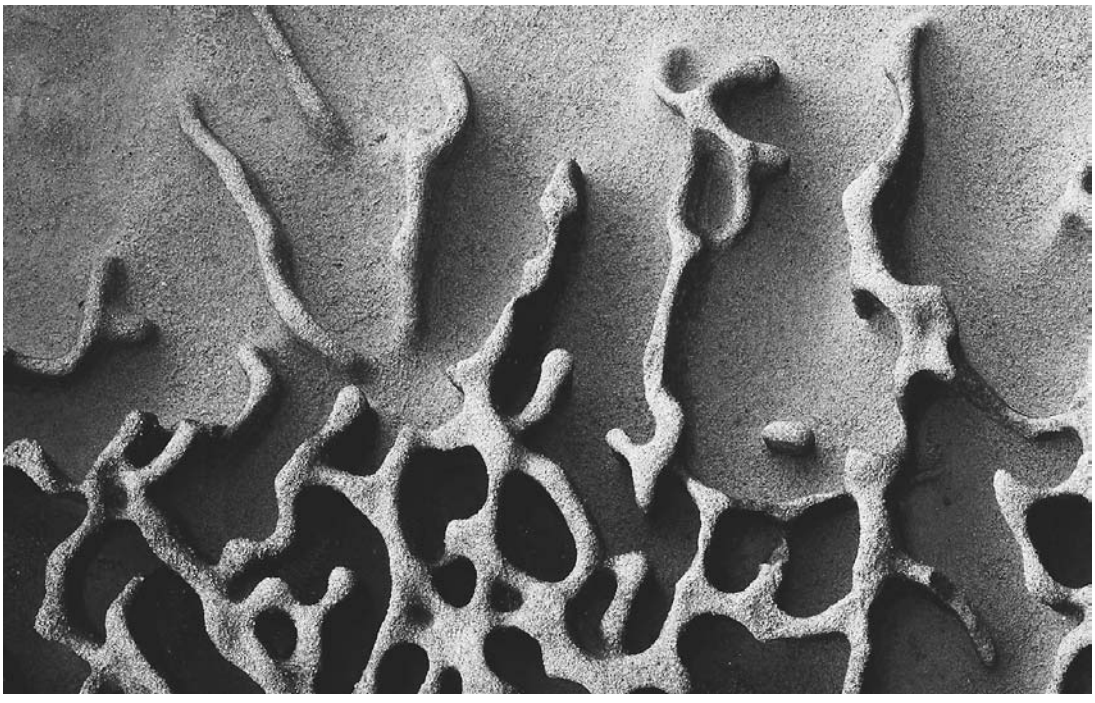
**UNDERSTANDING THE SPHERES.** In fact, each sphere represents a sector of existence on the planet that is at once clearly defined and virtually inseparable from the others. Each is an open system within the closed system of Earth, and overlap is inevitable. For example, the seeds of a plant (biosphere) 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 $6 \times 10^{21}$ 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.

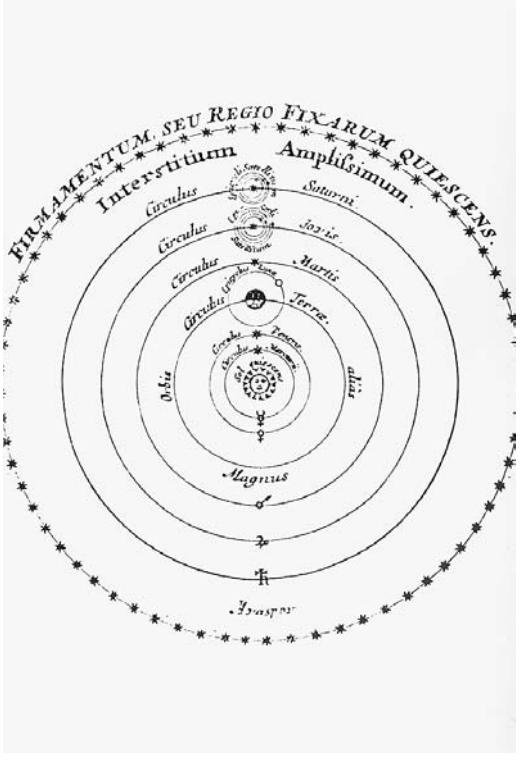



Diagram showing the solar system as Copernicus envisioned it, with the sun at the center. The Copernican system heralded the start of the Scientific Revolution. *(© Dr. Jeremy Burgess/Photo Researchers. Reproduced by permission.)*

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.

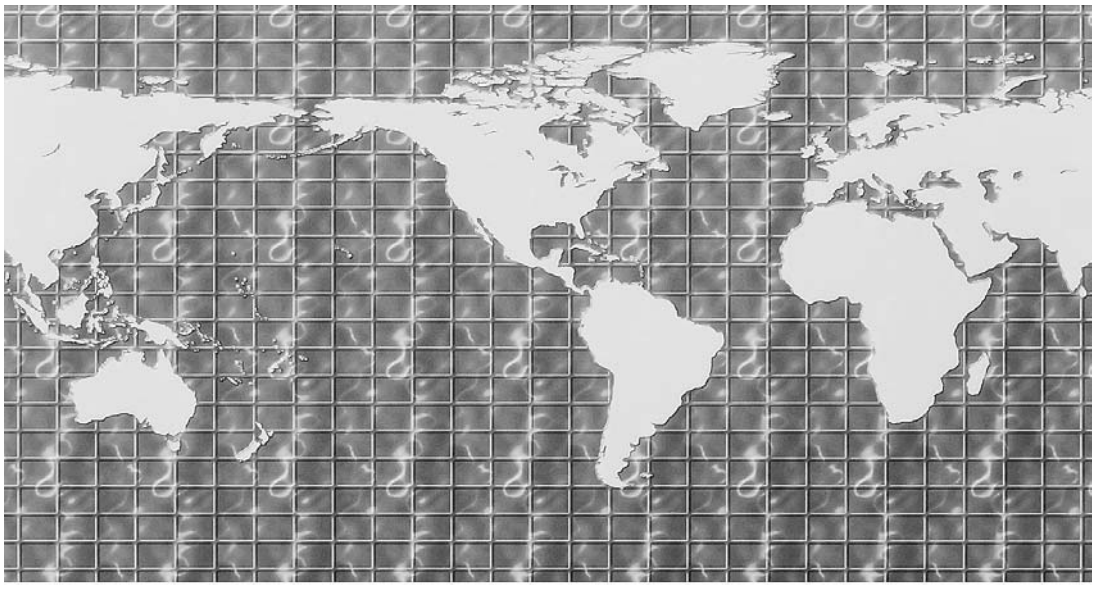
**PTOLEMY'S GEOGRAPHY.** Unfortunately, the Alexandrian astronomer Ptolemy (*ca.* A.D. 100–170), one of the most influential figures of the ancient scientific world, rejected Eratosthenes' calculations and performed his own, based on faulty information. The result was a wildly inaccurate estimate of 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

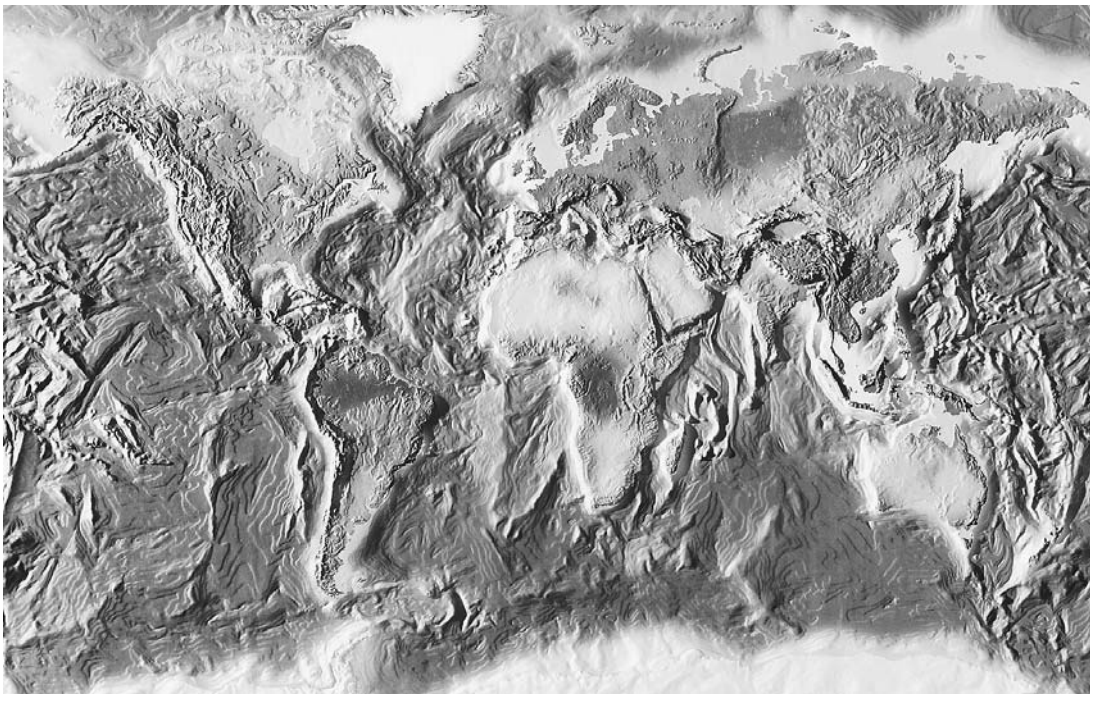
A geologic map shows the rocks beneath Earth's surface, including their distribution according to type as well as their ages, relationships, and structural features. The first geologic map, made in 1743, depicted subterranean East Kent, England. Its creator, the English physician and geologist Christopher 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

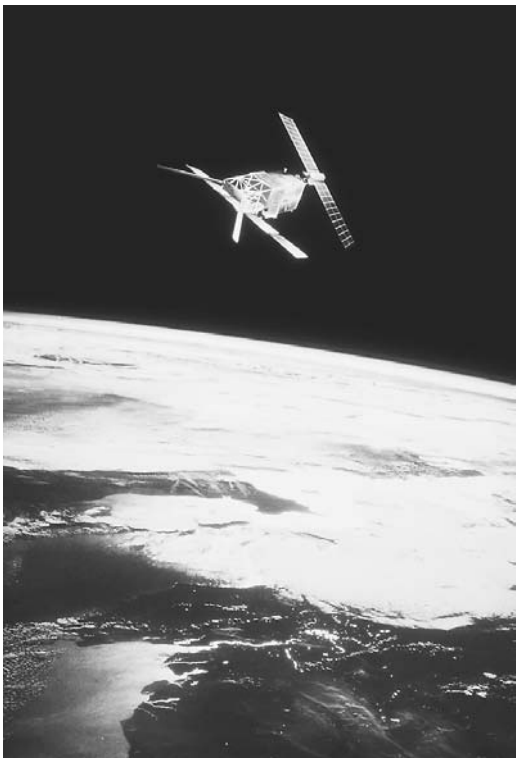
aircraft during World War II, for instance, photogeologic data gathering has increased dramatically in the years since then. Efforts at gaining information by means of airborne sensing devices underwent enormous improvements throughout the middle and latter part of the twentieth century, with the development 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.

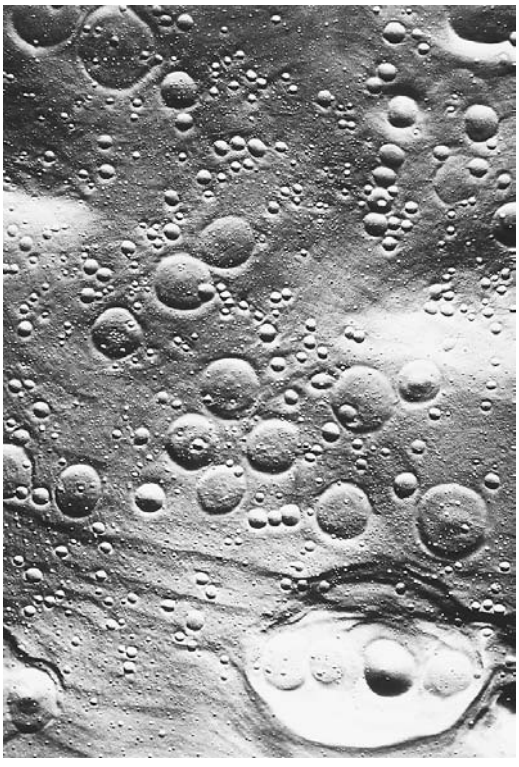
By contrast, the Moon has a diameter of only about 2,160 mi. (3,475 km), a little less than the distance from New York to Los Angeles. Its mass is a little more than 1% of Earth's, and as a result, its gravitational pull is too small to retain the gases that make up the atmosphere. That small mass, combined 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 ($4.5 \times 10^6$ 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 $1.66 \times 10^{-24}$ 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

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# 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

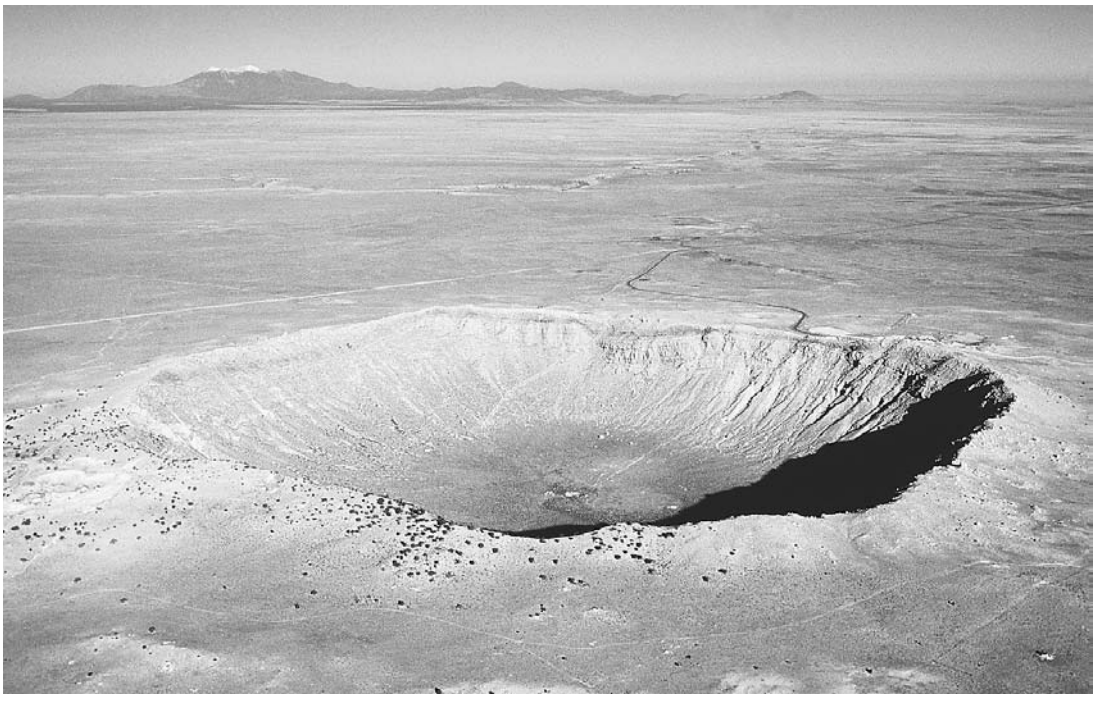
### Uniformitarianism

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 $7.038 \times 10^8$ 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.

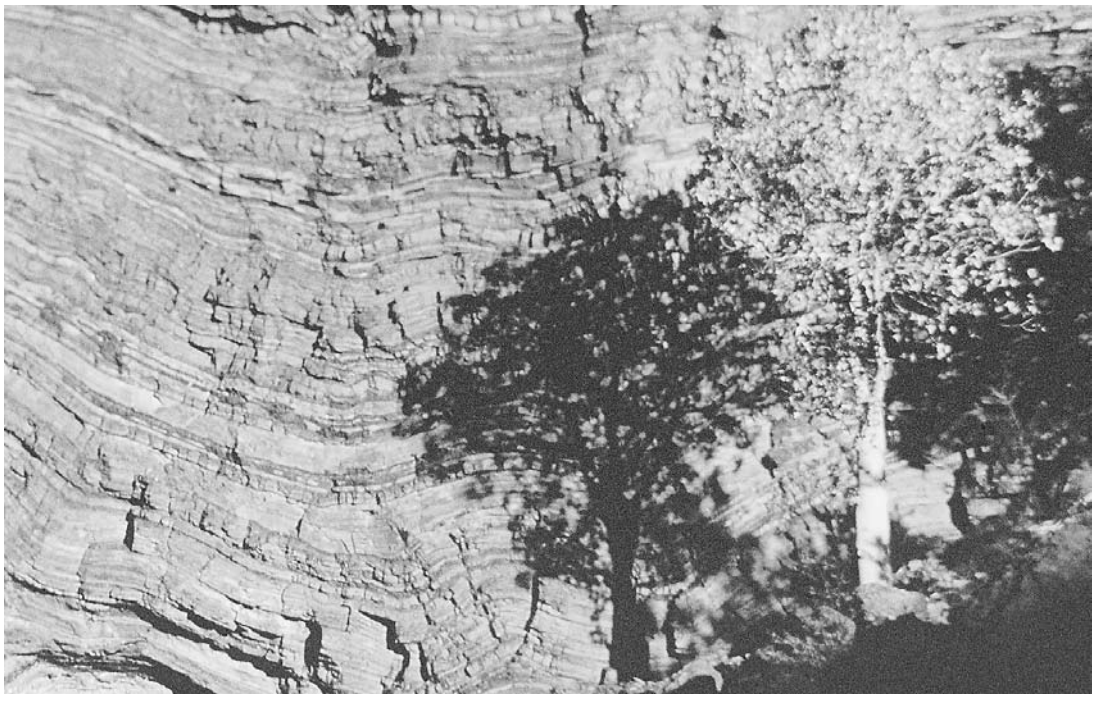
## REAL-LIFE APPLICATIONS

### 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 $4.47 \times 10^9$ 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

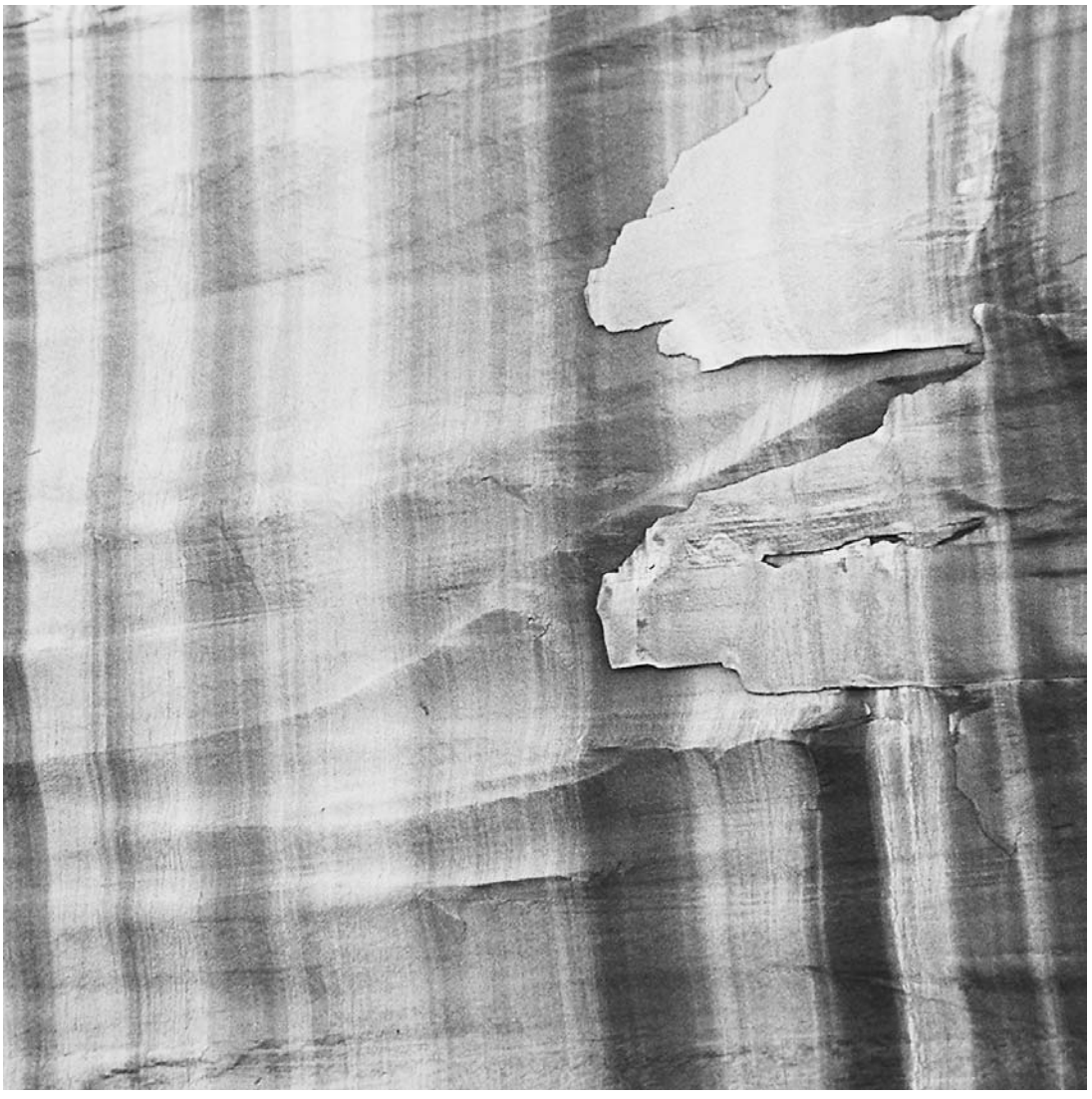
Historical geology, the study of Earth's physical history, is one of the two principal branches of geology, the other being physical geology, or the study of Earth's physical components and the forces that have shaped them. Among the principal subdisciplines of historical geology is stratigraphy, the 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:

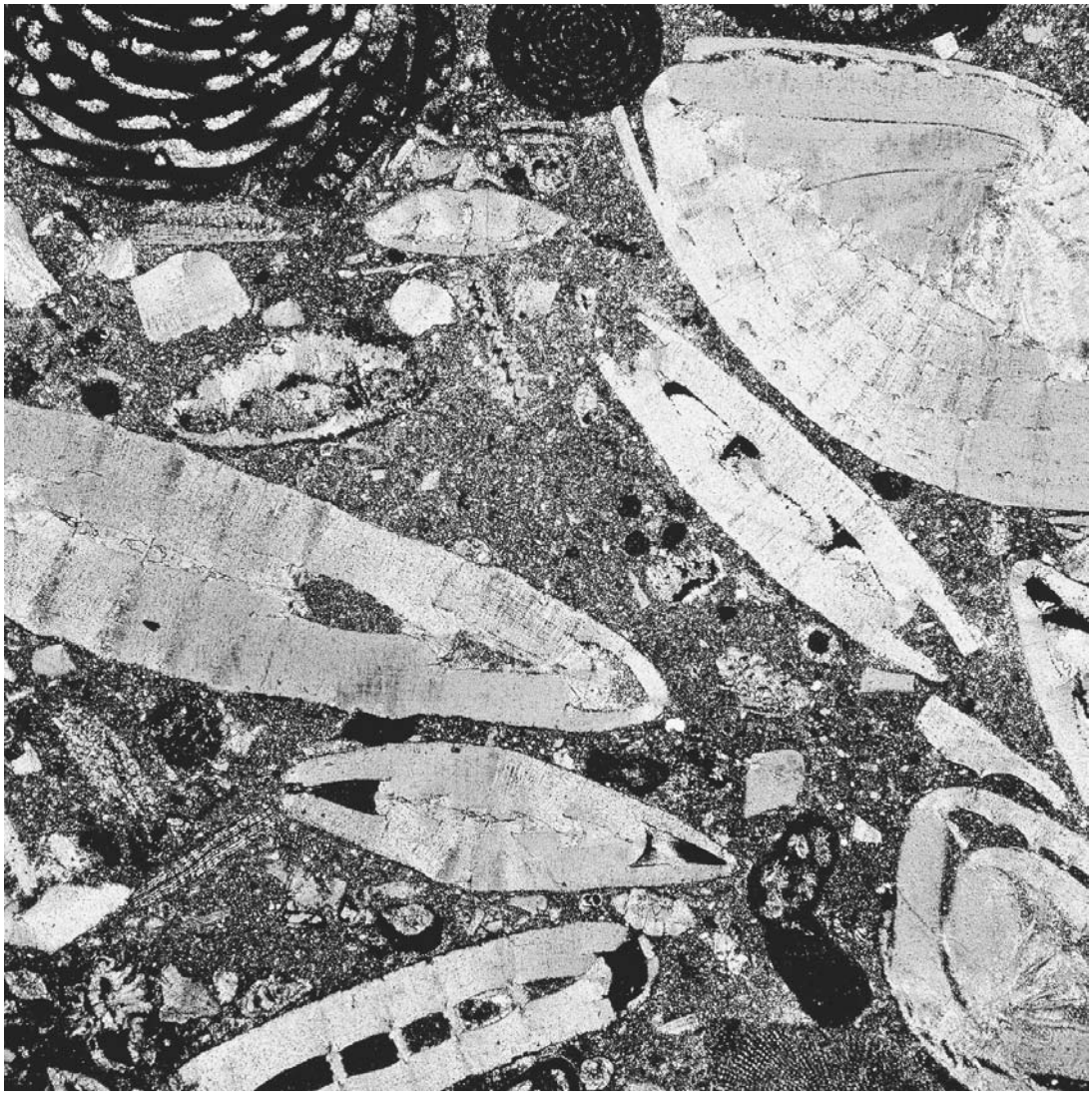
Epochs/Series of the Cenozoic Era/Erathem

- 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).

## WHERE TO LEARN MORE


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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."

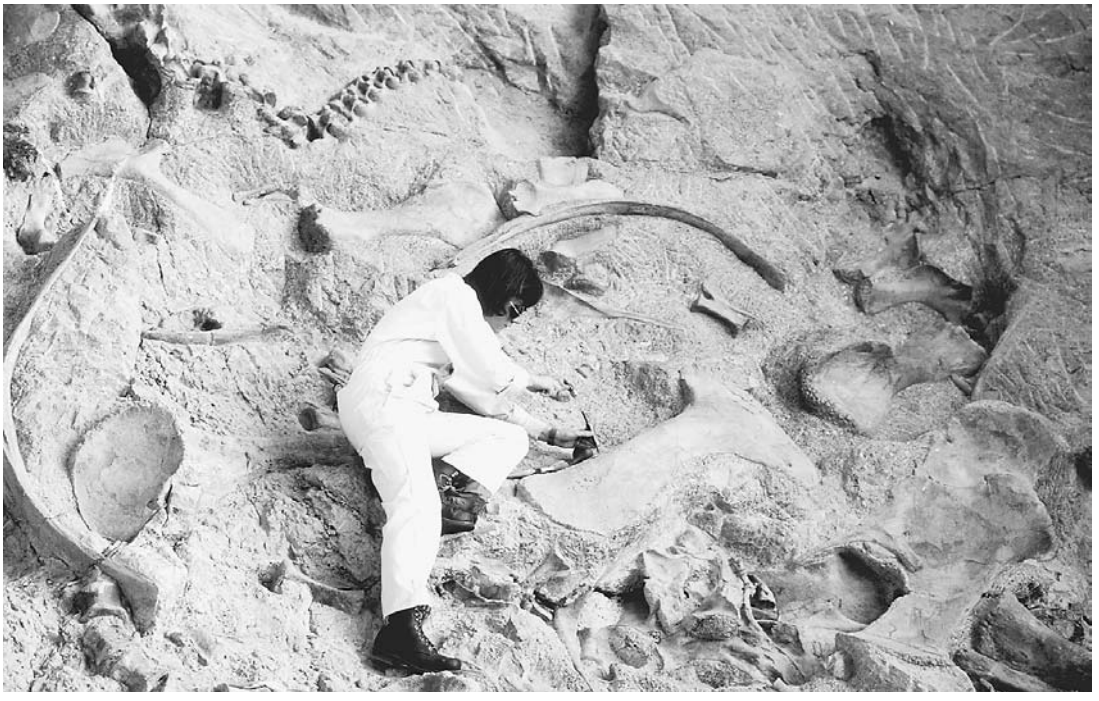
**Epochs of the Cenozoic era.** An epoch is the fourth-largest division of geologic time and is, for the most part, the smallest one with which we will be concerned. (There are two smaller categories, the age and the chron.) Listed here are the epochs of the Cenozoic era from the most distant to the 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.

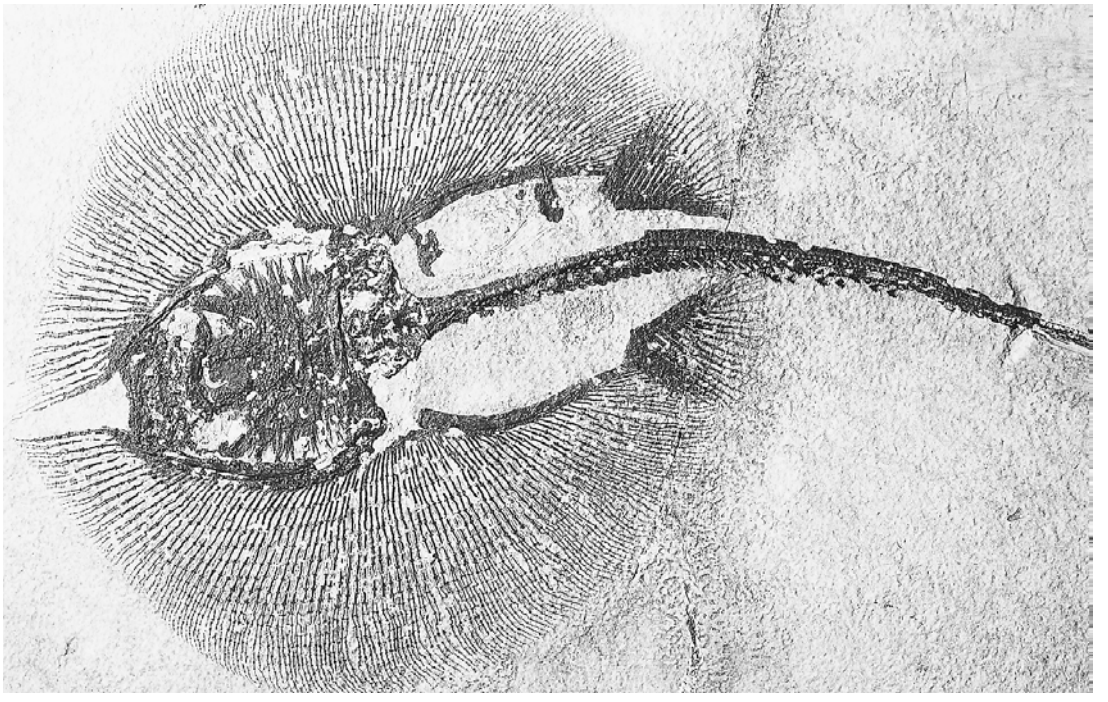
When an organism is alive, it incorporates a certain ratio of carbon-12 in proportion to the (very small) amount of carbon-14 that it receives from the atmosphere. Once the organism dies, however, it stops incorporating new carbon, and the ratio between carbon-12 and carbon-14 begins to change as the 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.

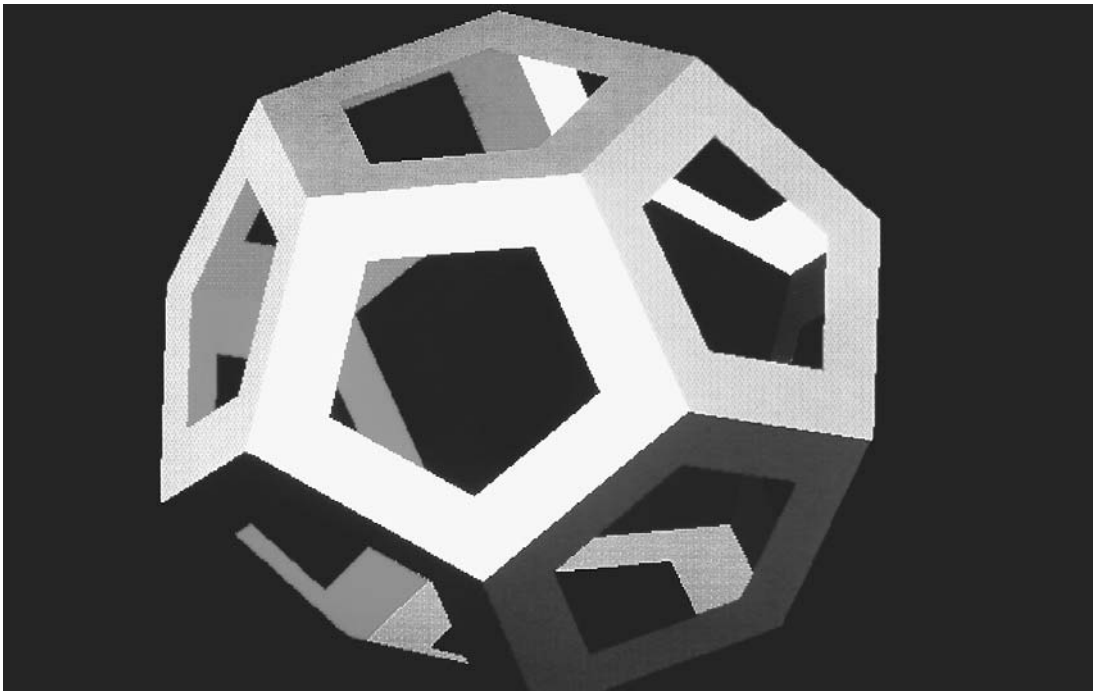
The term crystal is popularly associated with glass and with quartz, but only one of these is a crystalline solid. Quartz is a member of the silicates, a large group of minerals that we will discuss later in this essay. Glass, on the other hand, is an amorphous solid, meaning that its molecules are not 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.)

## WHERE TO LEARN MORE

*Atlas of Rocks, Minerals, and Textures* (Web site). <http://www.geosci.unc.edu/Petunia/IgMetAtlas/mainmenu.html>.

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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.

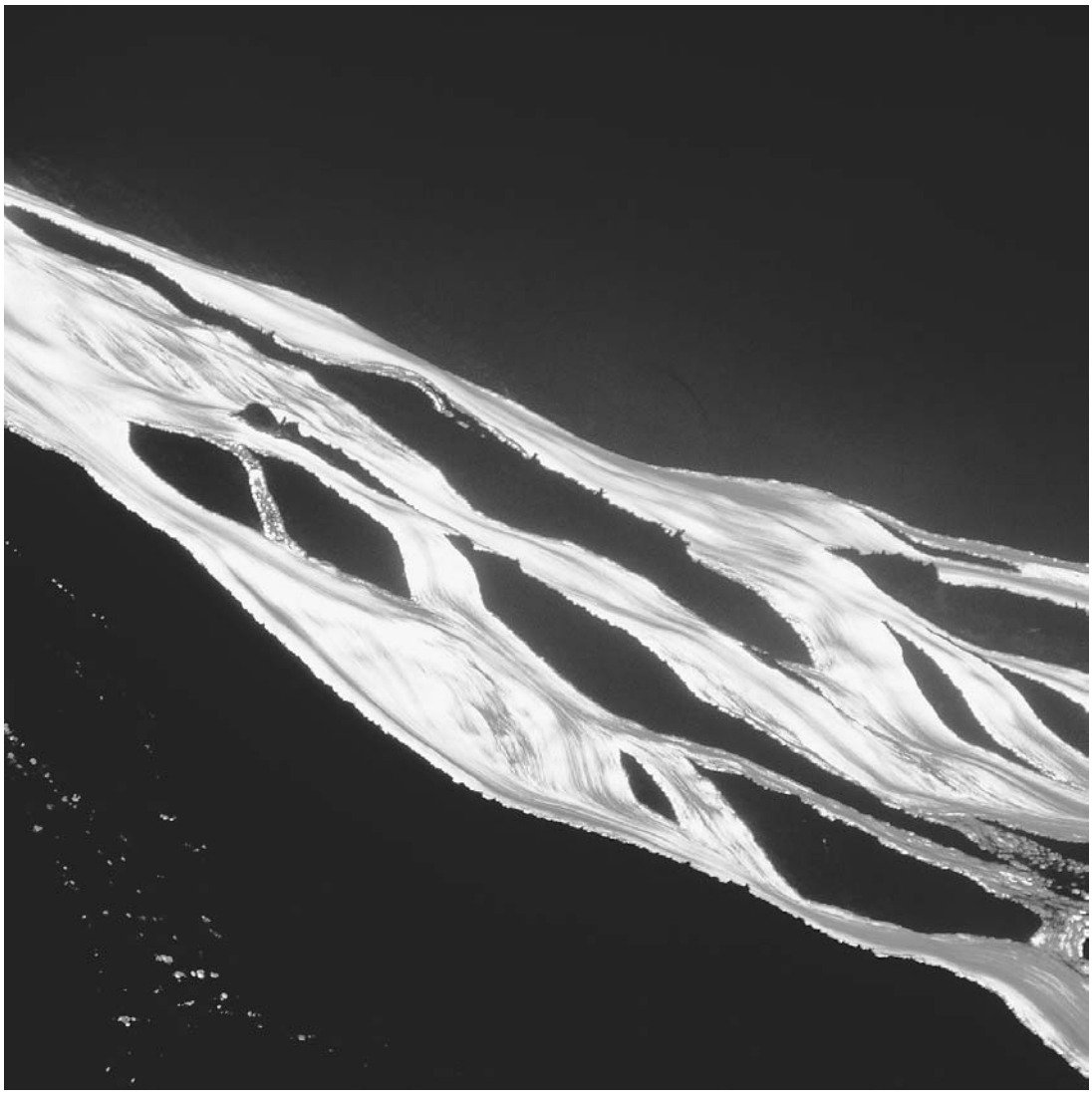
Still later, medieval Europe built its cathedrals and castles of stone, though it should be noted that the idea of the castle came from the Middle East, where the absence of lumber for fortresses caused Syrian castle builders to make use of abundant sandstone instead. Other societies left behind their 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.

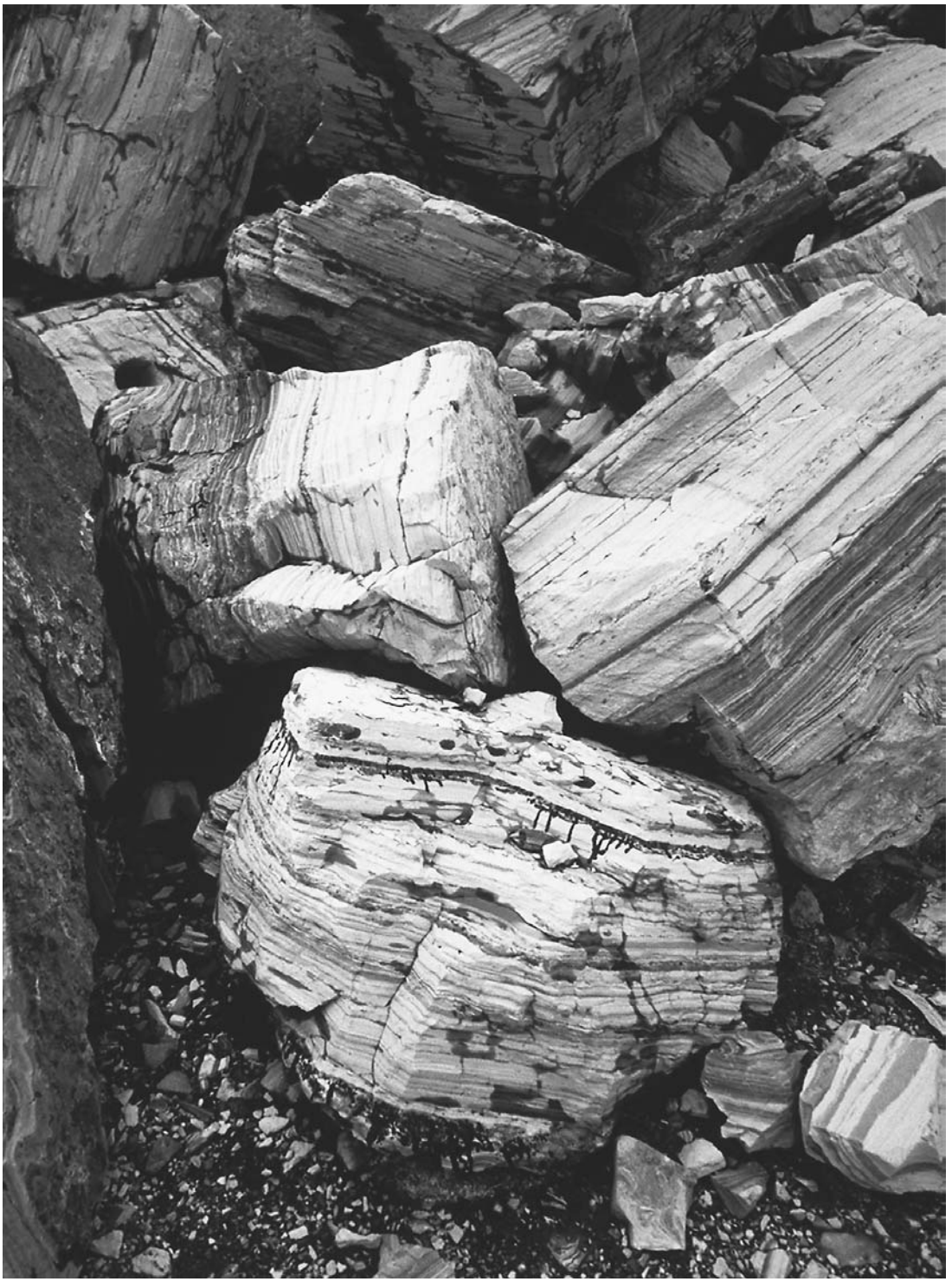
Once generated, petroleum gradually moves from the source rock to a reservoir rock, or a rock that stores petroleum in its pores. A good reservoir rock is one in which the pore space constitutes more than 30% of the rock volume. Yet the rock must be sealed by another rock that is much less porous; indeed, 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.

## WHERE TO LEARN MORE

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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.

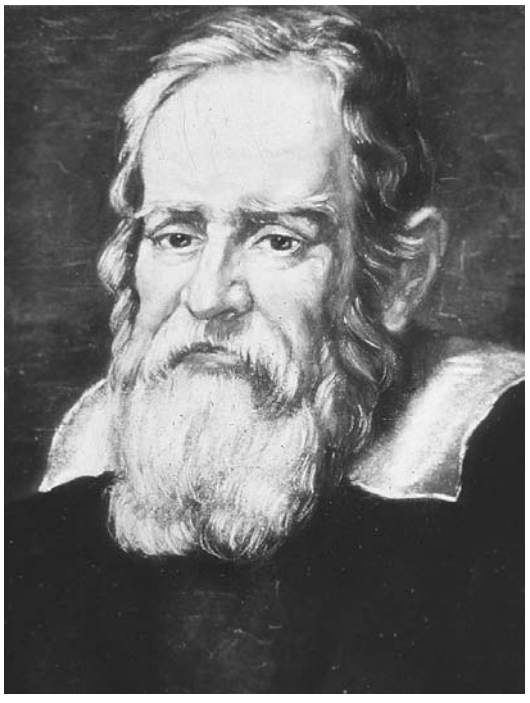
Thanks to gravity, all objects on Earth as well as those within its gravitational field remain fixed in place. These objects include man-made satellites, which have grown to number in the thousands since the first was launched in 1957, as well as the greatest satellite of them all: the Moon. Even though 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 $6.67 \times 10^{-11}$—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: $5.98 \times 10^{24}$ 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

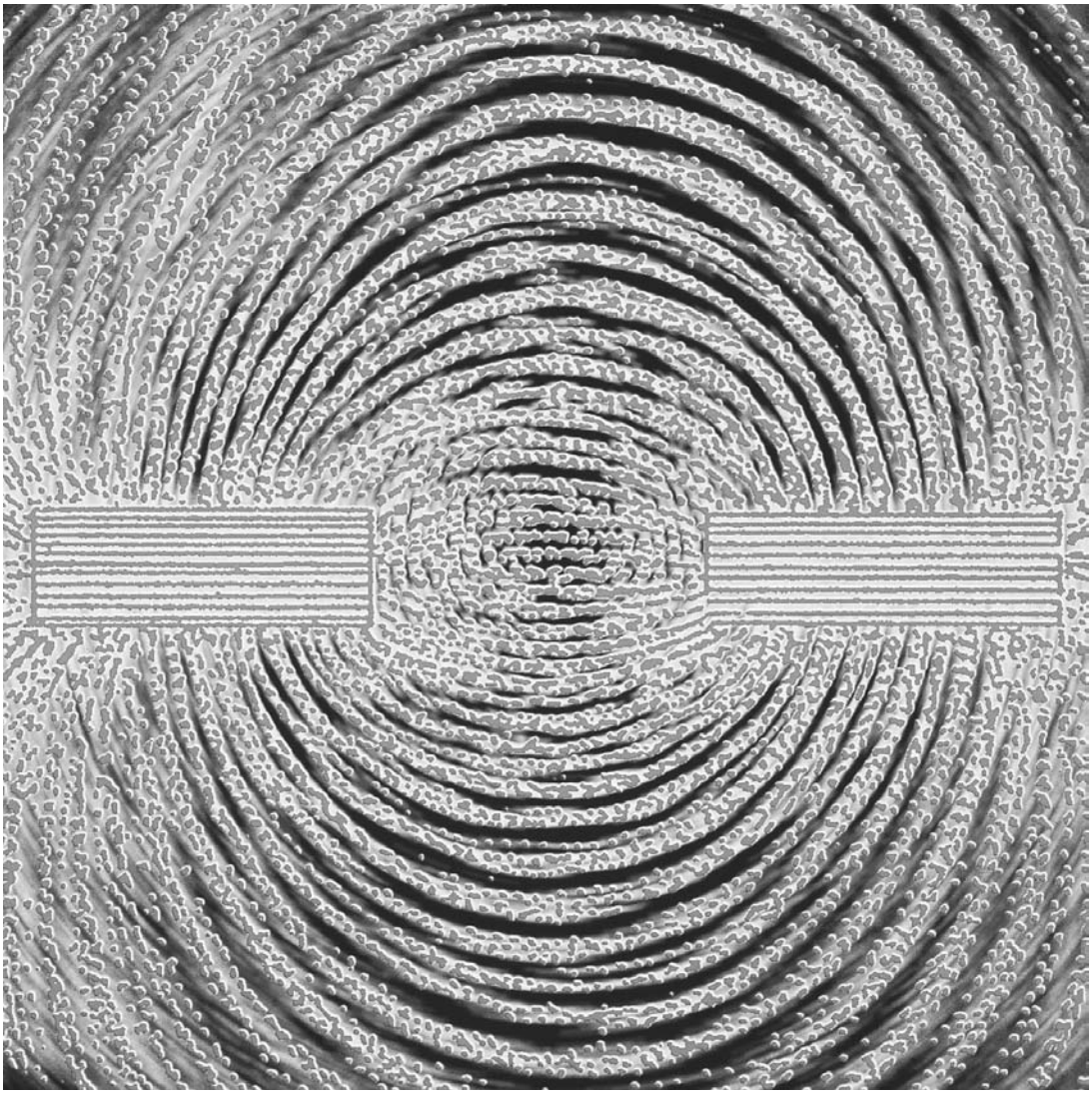
### Electromagnetism

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 $5 \times 10^{-5}$ 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.

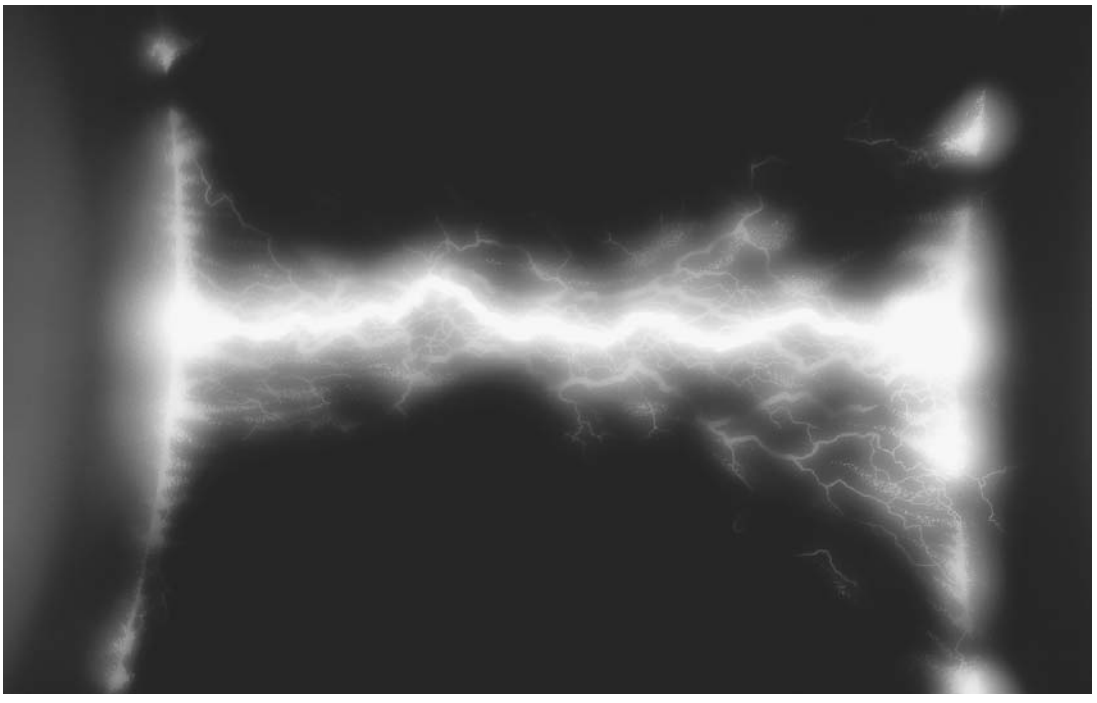
**THE MAGNETOSPHERE.** Surrounding the planet is a vast region called the magnetosphere, an area in which ionized particles (i.e., ones that have lost or gained electrons so as to acquire a net electric charge) are affected by Earth's magnetic field. The magnetosphere is formed by the interaction between 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.

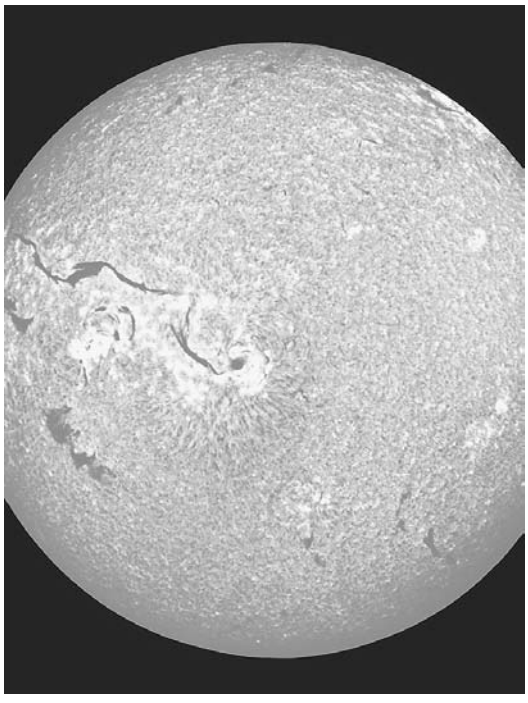
On a vastly greater scale, convective cells are present in the Sun. These vast cells appear on the Sun's surface as a grainy pattern formed by the



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 $2.8 \times 10^{-10}$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

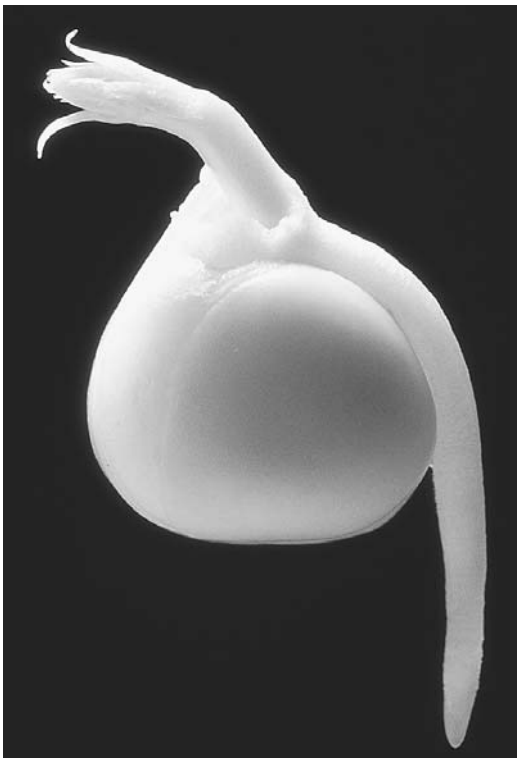
could add all those energy components together, one would find that all the energy that entered the system left the system. Note, however, that once again the process is irreversible: one can use gasoline to power a battery and hence a car radio, but the radio or the battery cannot generate gasoline.

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.

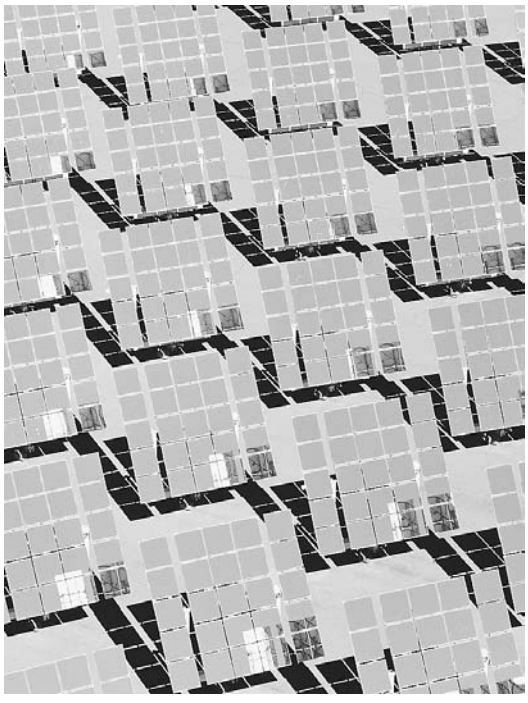
Also, fears about Earth running out of fuel are built on the assumption that no one will develop other sources of energy, a few of which are discussed at the conclusion of this essay. Though most of the known alternative energy sources face their own challenges, it is thoroughly conceivable that scientists 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 ($3.6 \times 10^6$) 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.

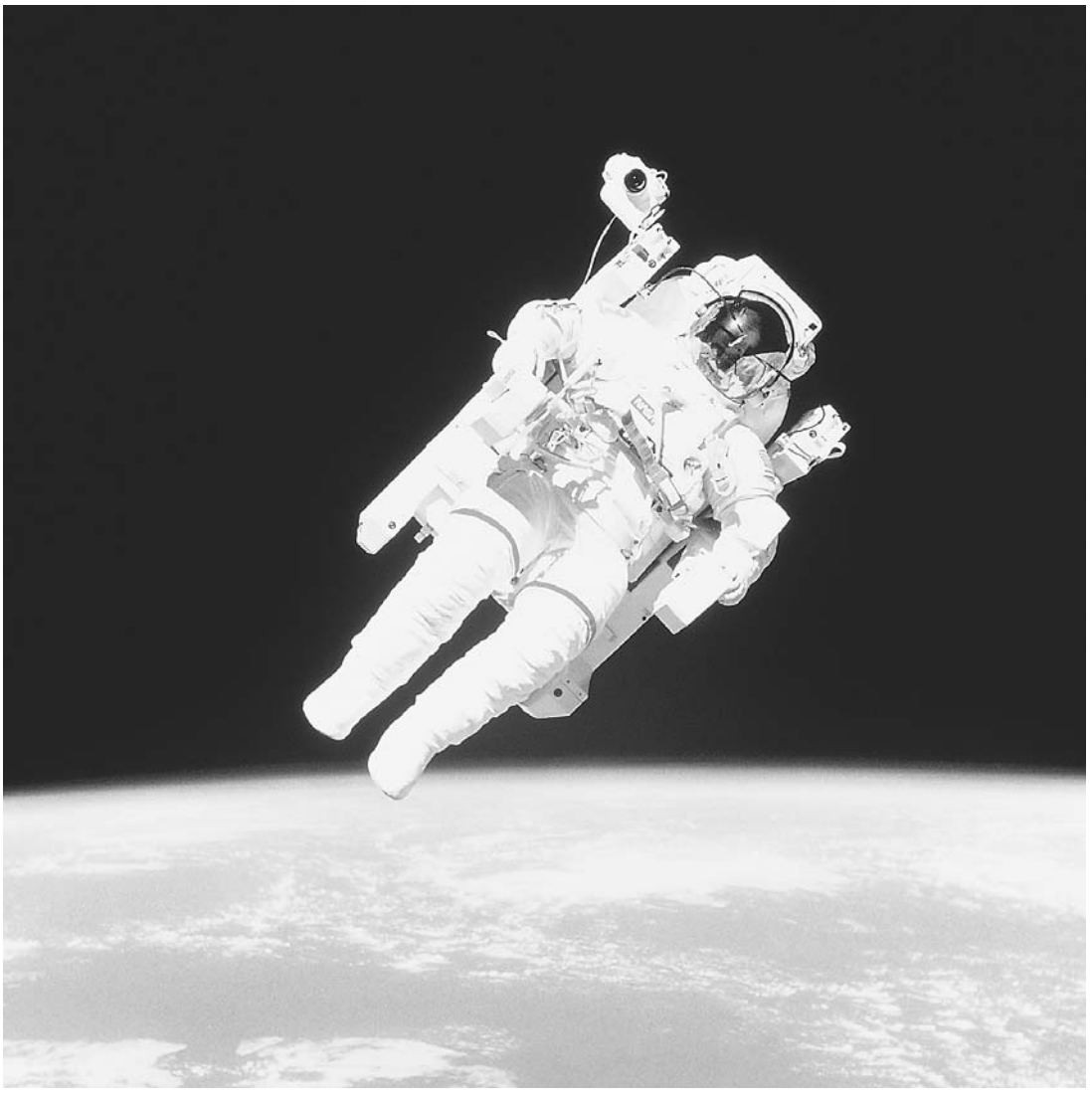
The Gutenberg discontinuity, or the core-mantle boundary (CMB), marks our entrance to the core. By now it has become very, very hot. Whereas the lithospheric mantle is about 1,600°F (870°C), the bottom of the lithosphere is about 4,000–6,700°F (2,200–3,700°C). By the time we get to the inner core, we 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).

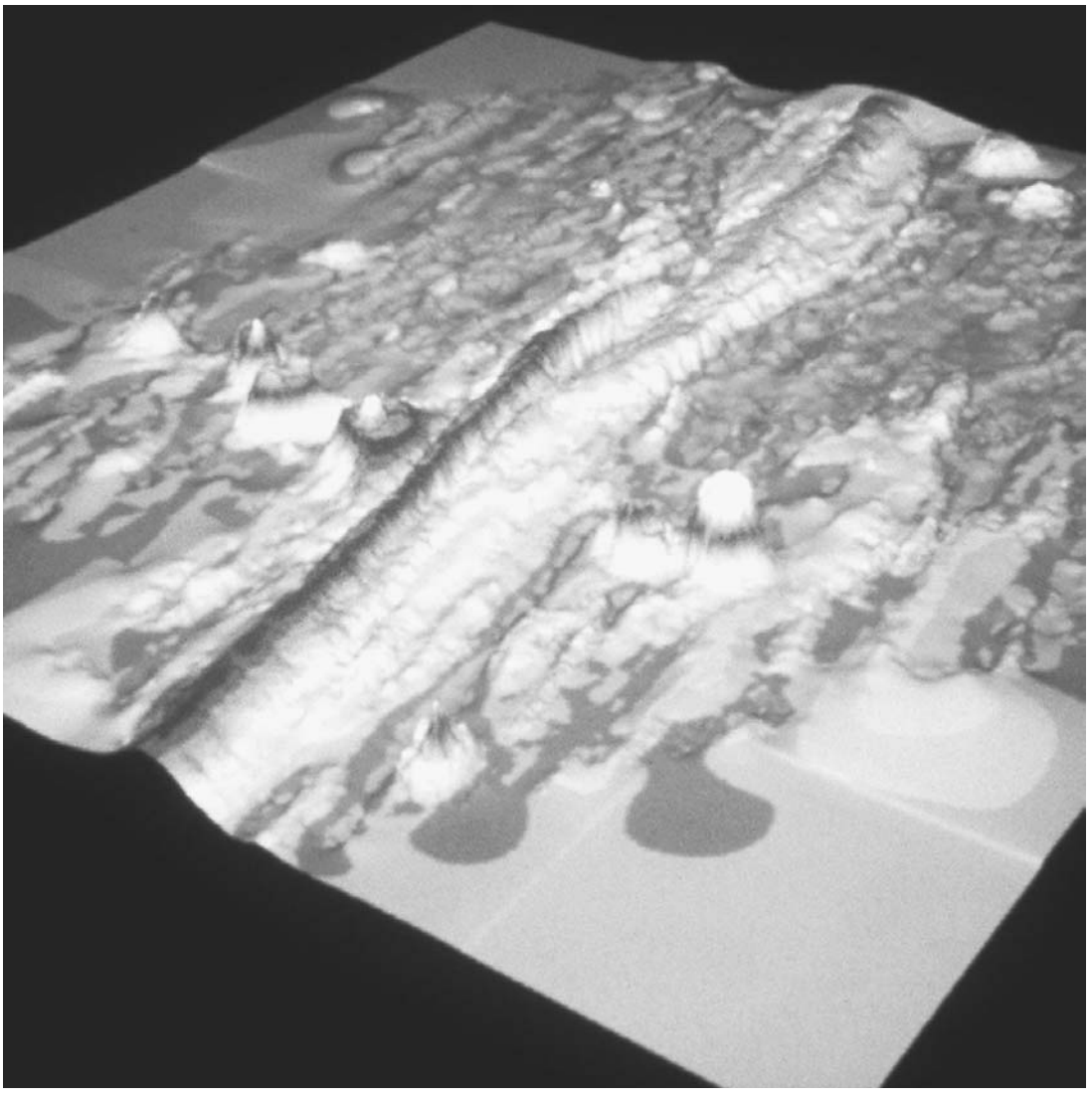
**PANGAEA, LAURASIA, AND GONDWANALAND.** According to Wegener, the continents of today once formed a single supercontinent called Pangaea, from the Greek words *pan* ("all") and *gaea* ("Earth"). Eventually, Pangaea split into two halves, with the northern continent of Laurasia and the southern continent 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.

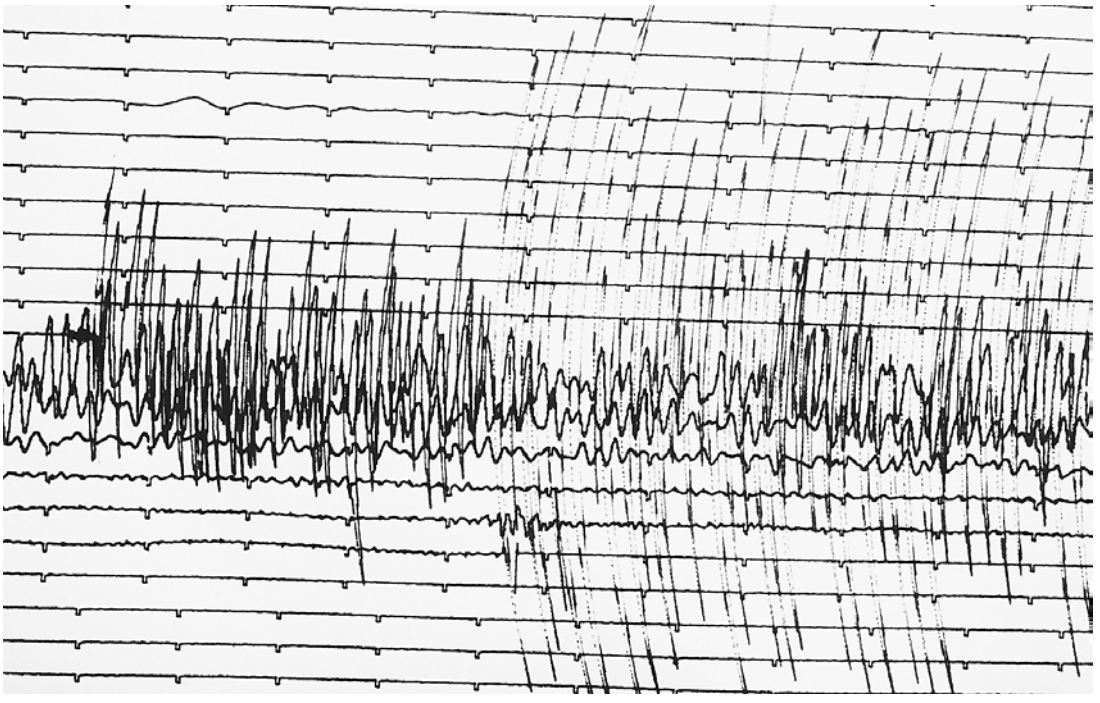
It so happens that this area is home to an unusual amount of volcanic activity. Southern California, where the North American and Pacific plates meet on the San Andreas fault, also is extremely prone to earthquakes, as is Japan, whose islands straddle the Philippine, Eurasian, and Pacific plates. Hawaii 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

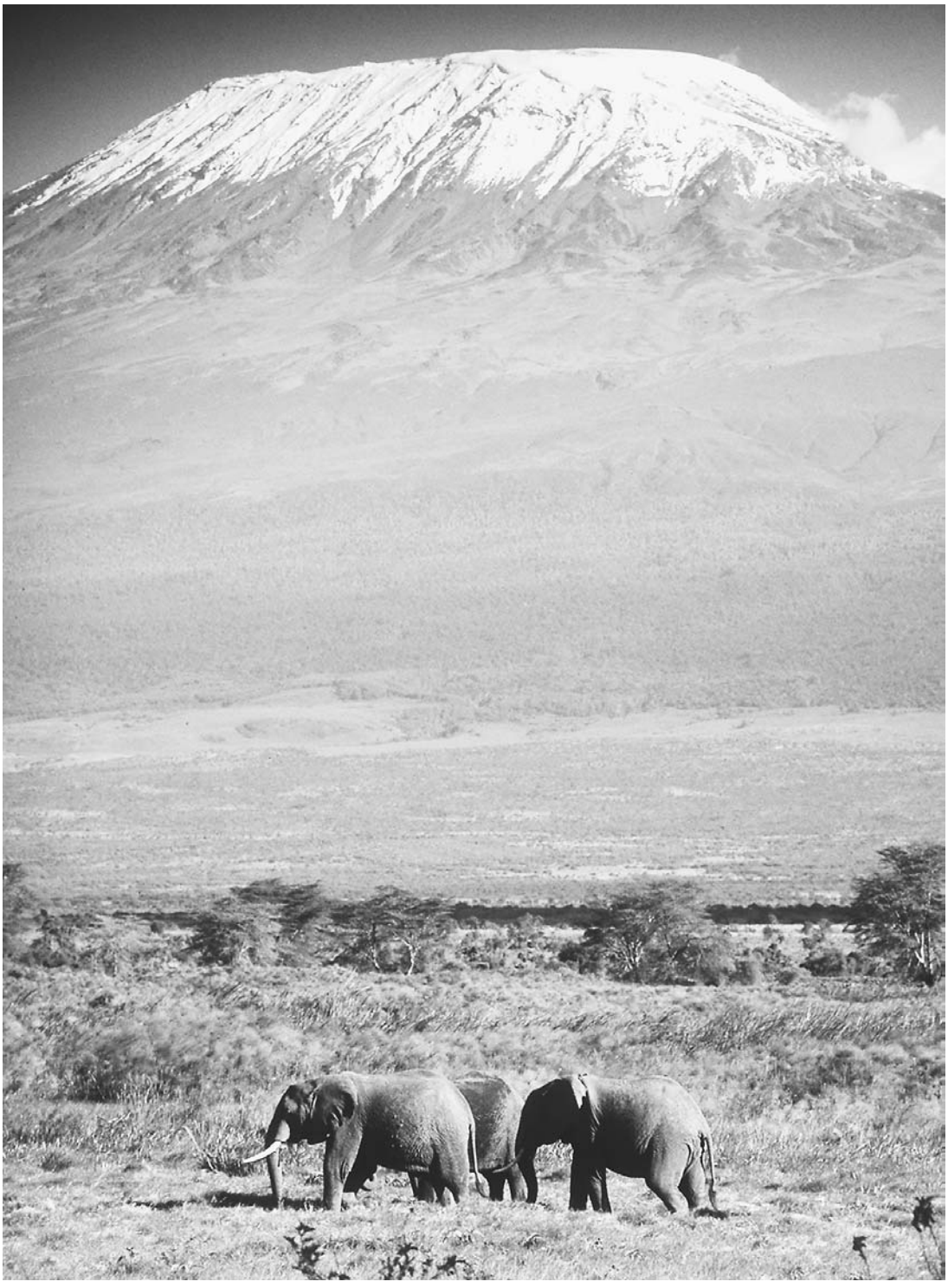
Earth is constantly moving, driven by forces beneath its surface. The interior of Earth itself is divided into three major sections: the crust, mantle, and core. The lithosphere is the upper layer of Earth's interior, including the crust and the brittle portion at the top of the mantle. Tectonism is 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.

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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

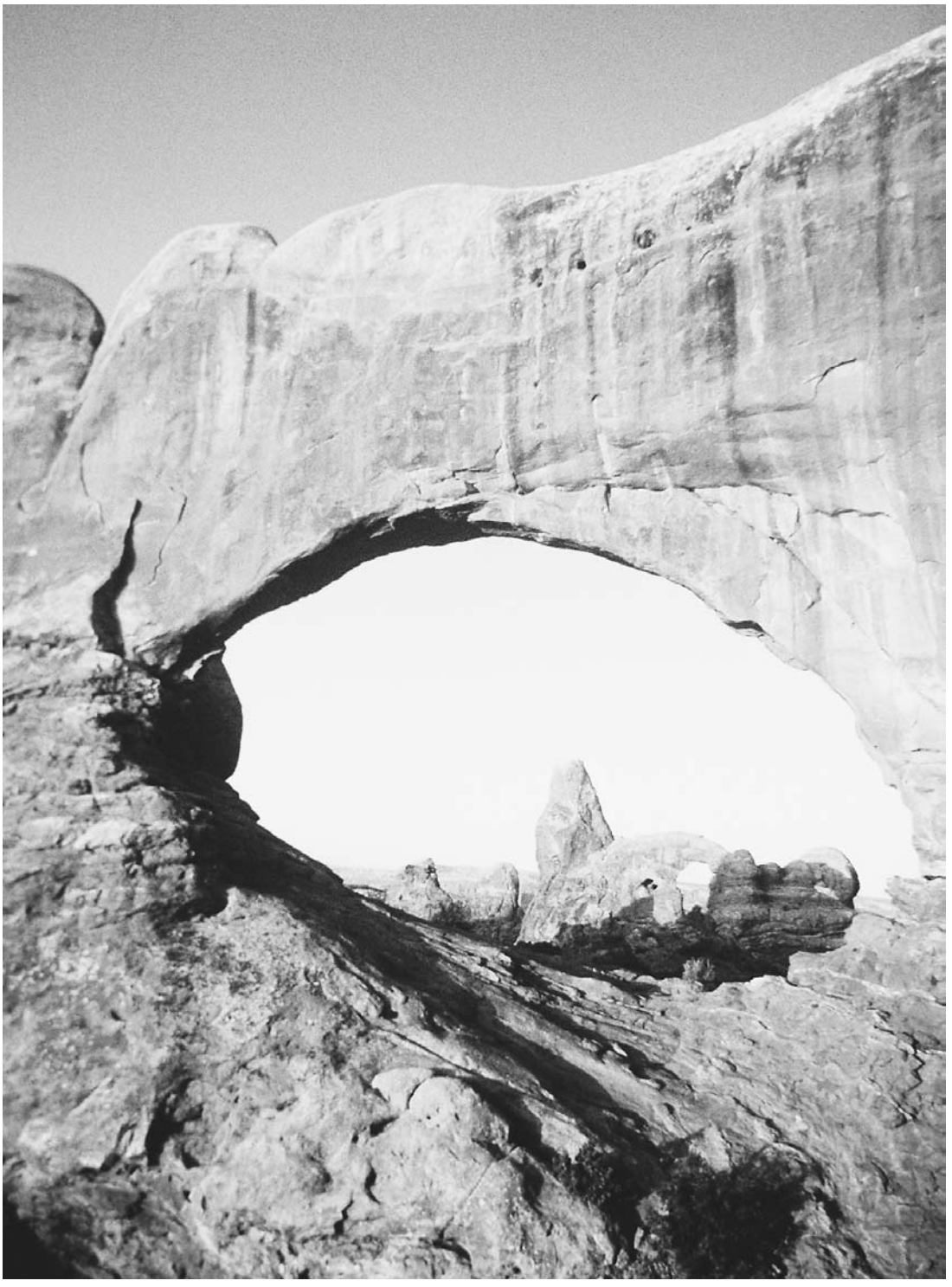
One of the principal sources of erosion is gravity, which is also the force behind creep, the slow downward movement of regolith along a hill slope. The regolith begins in a condition of unstable equilibrium, like a soda can lying on its side rather than perpendicular to a table's surface: in both cases, 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

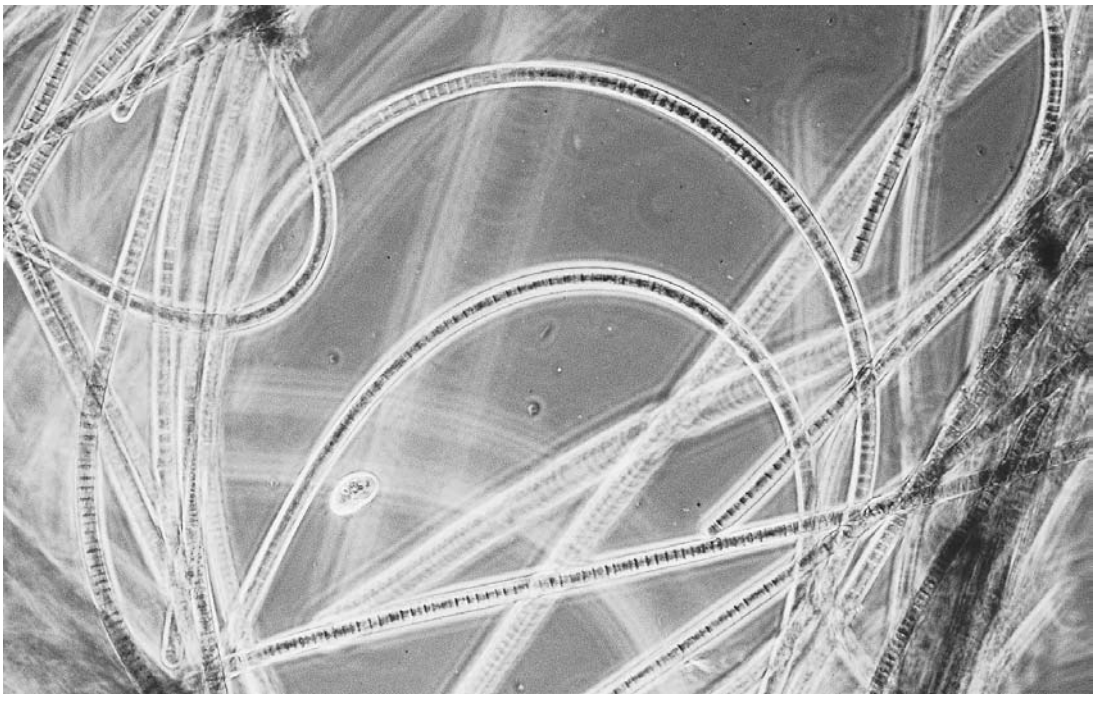
### The Beginnings of Soil Formation

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.

**PARENT MATERIAL:** Mineral fragments removed from rocks by means of weathering. Along with organic deposits, these fragments 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.

**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).

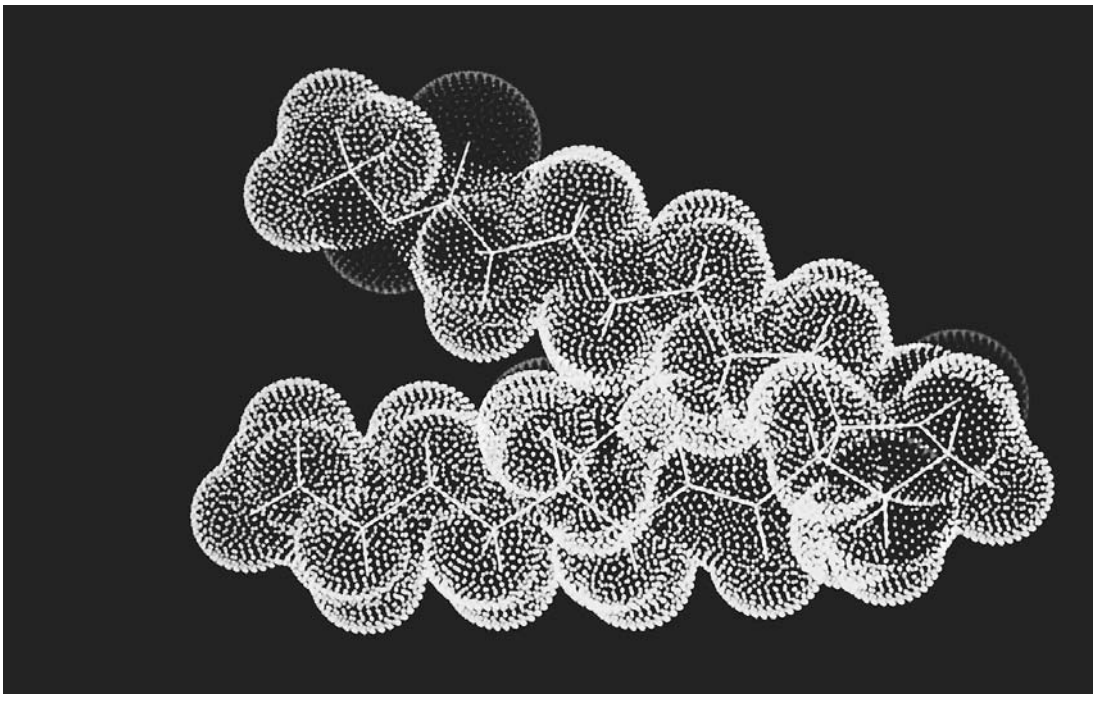
## Chemistry and Geochemistry

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

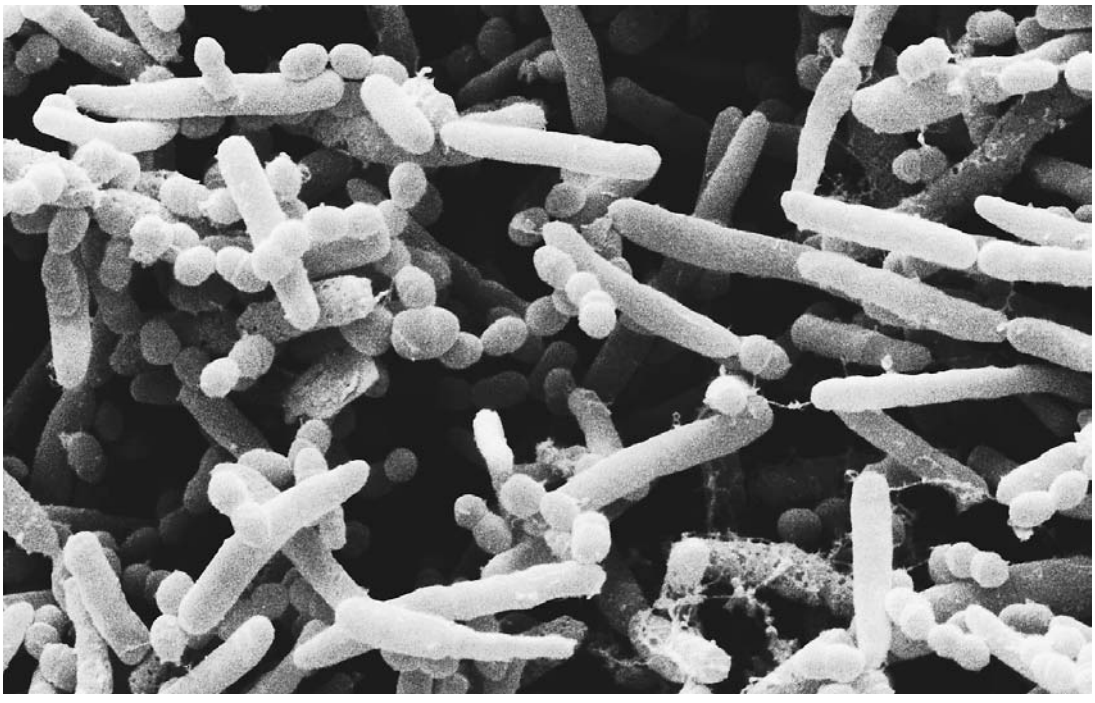
Just as geochemistry is a branch of the geologic sciences that weds physics and geology, so there is a geologic subdiscipline, geochemistry, in which chemistry and the geologic sciences come together. Geochemistry is concerned with the chemical properties and processes of Earth—in particular, the abundance 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.

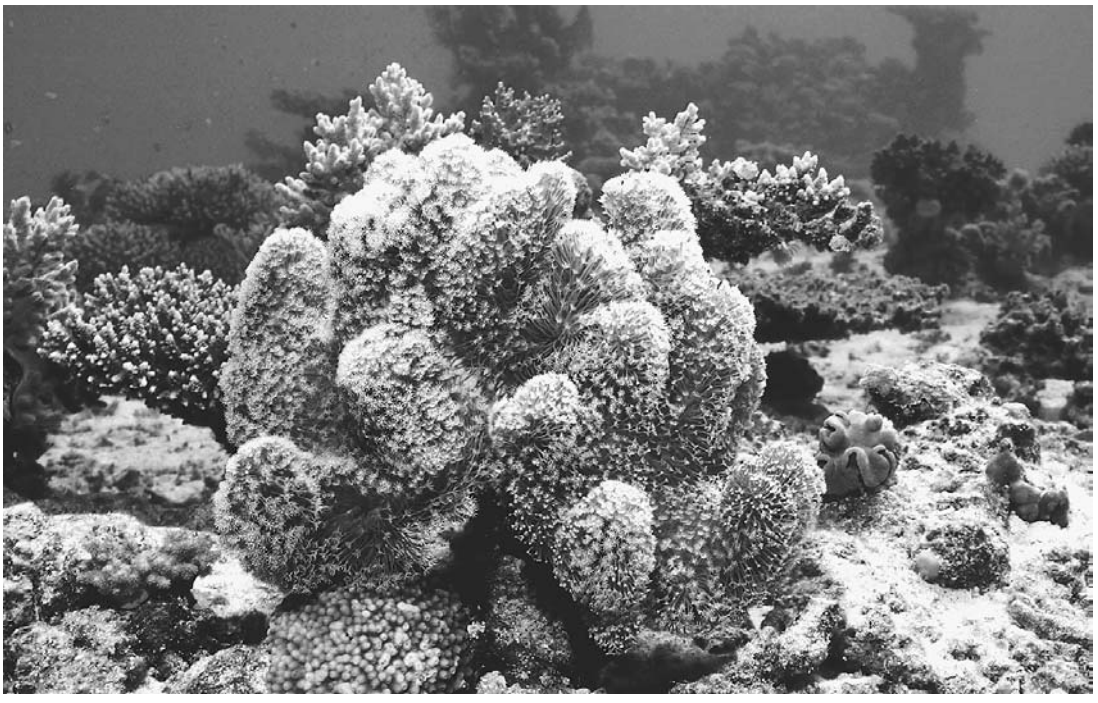
Organic chemistry encompasses the study of many things that people commonly think of as "organic"—living creatures, formerly living creatures, and the parts and products of their bodies—but it also is concerned with substances that seem quite far removed from the living world. Among these substances 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

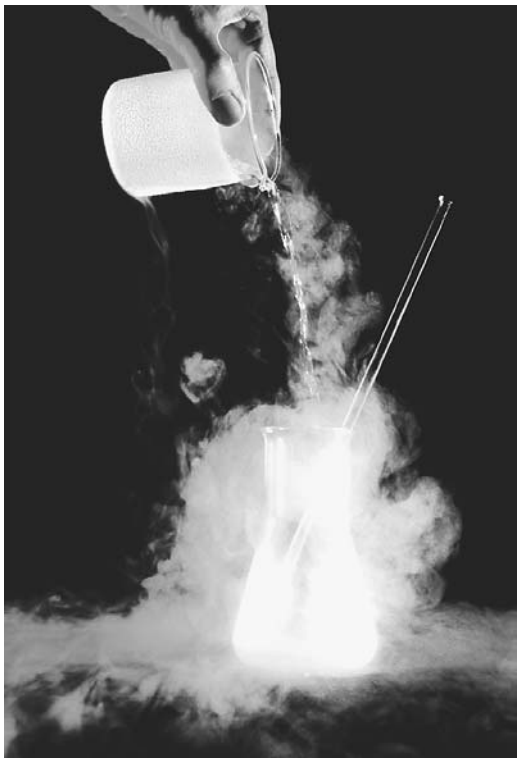
### Chemistry and Elements

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.

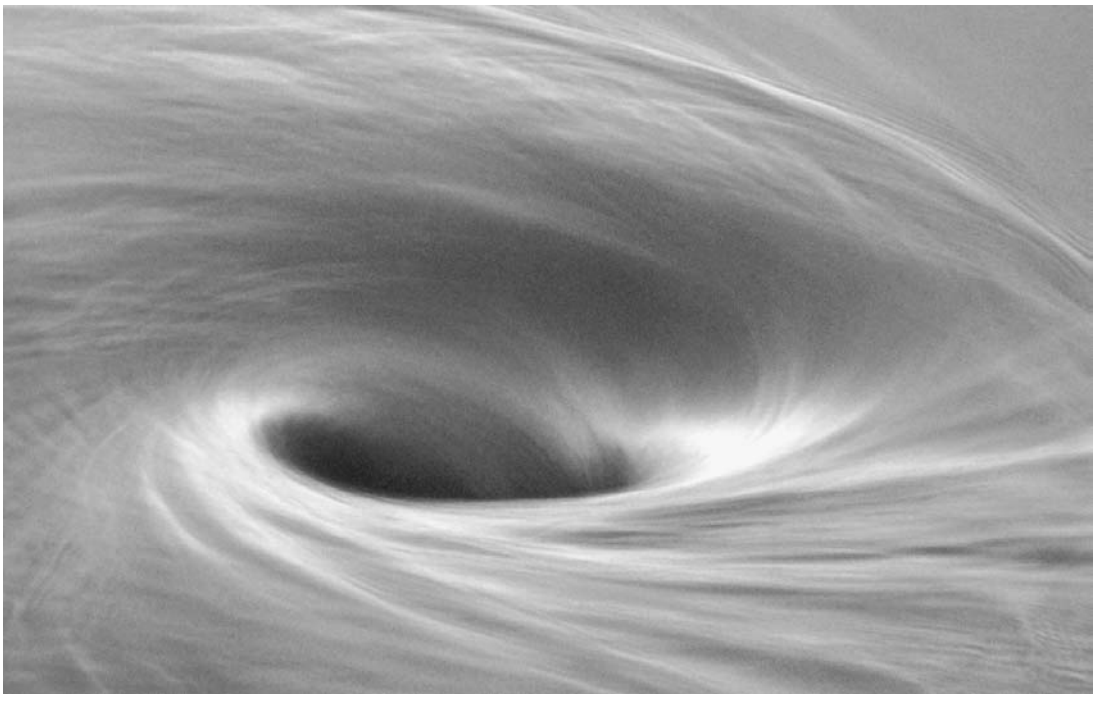
## Introduction to Hydrology

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

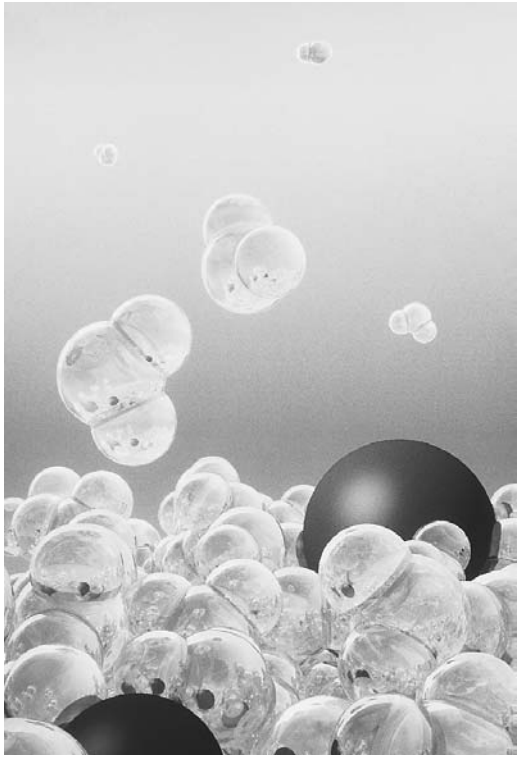
As we have noted, water and the hydrosphere are practically synonymous, but not completely so. The hydrosphere is the sum total of water on Earth, except for that portion in the atmosphere. This combines all water underground—which, as we shall see, constitutes the vast majority of water on the planet—as 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 $2.76 \times 10^{19}$ tons ($2.5 \times 10^{19}$ 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 $1.41 \times 10^{18}$ tons ($1.38 \times 10^{18}$ tonnes), or 5.2% of the total. Ice caps, glaciers, and icebergs contain $1.74 \times 10^{16}$ tons ($0.017 \times 10^{16}$ tonnes), thus accounting for most of the remaining 0.1% of Earth's water. Beyond these amounts are much smaller quantities representing shallow groundwater ($2.76 \times 10^{14}$ tons, or $2.5 \times 10^{14}$ tonnes); inland surface waters, such as lakes and rivers ($2.76 \times 10^{13}$ tons, or $2.5 \times 10^{13}$ tonnes); and the atmosphere ($1.43 \times 10^{13}$ tons, or $1.3 \times 10^{13}$ 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.

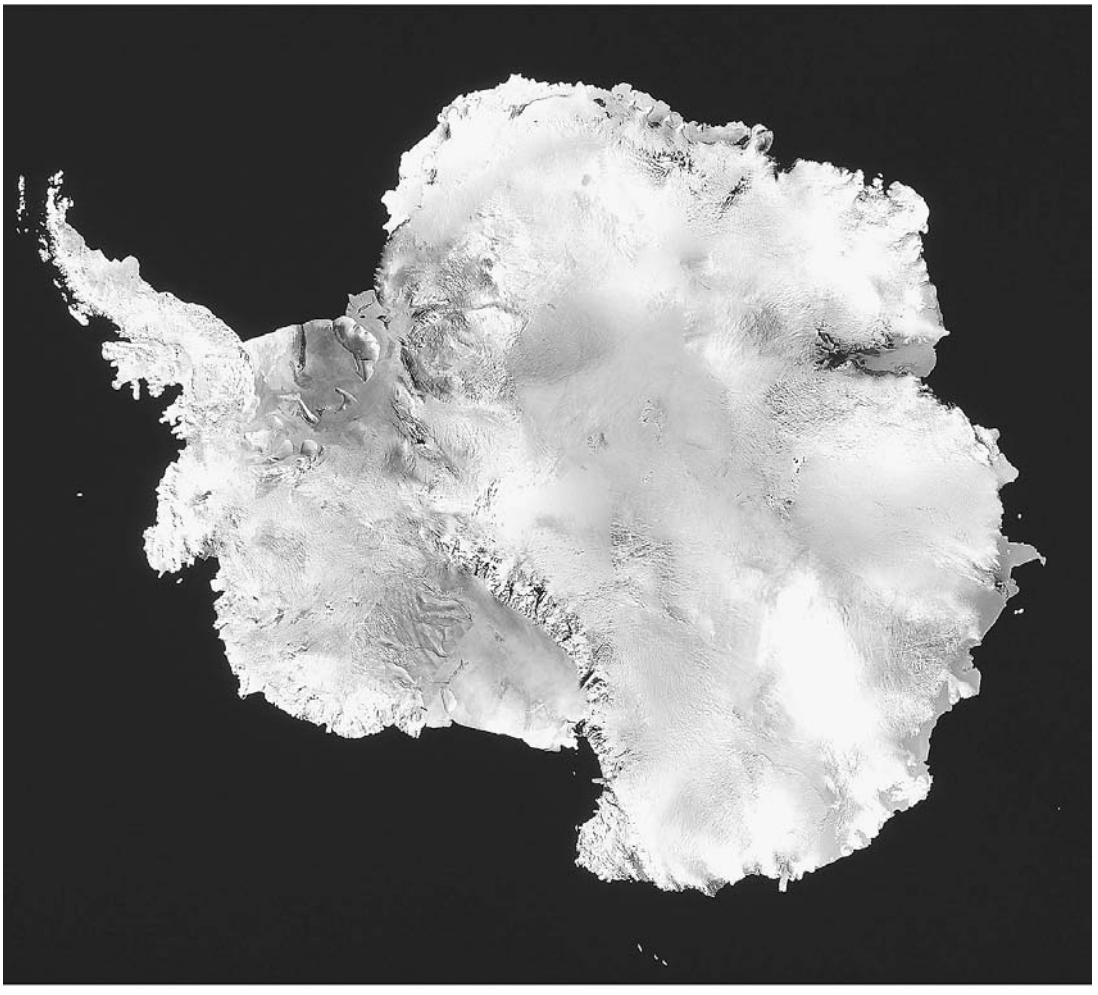
By definition, ice is composed of fresh water rather than saltwater. This is true even of icebergs, though they may float on the salty oceans. The reason is that water has a much higher freezing point than salt, and, therefore, when water freezes, very little of the salt remains joined to the water. 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.

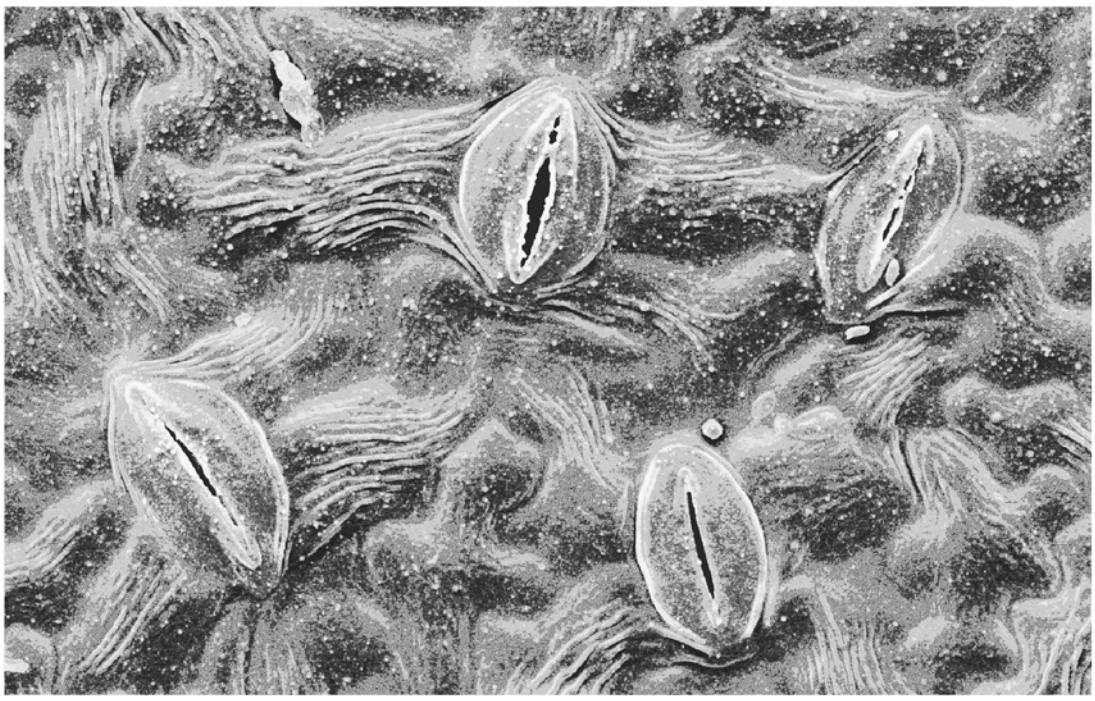
In evaporation, heat converts liquid water to a gaseous state, thus allowing it to be transferred to the atmosphere in the form of vapor. Whereas evaporation involves the loss of water to the atmosphere from nonliving sources, transpiration is the movement of water from living organisms to the atmosphere. 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 $1.433 \times 10^{13}$ tons ($1.3 \times 10^{13}$ 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.

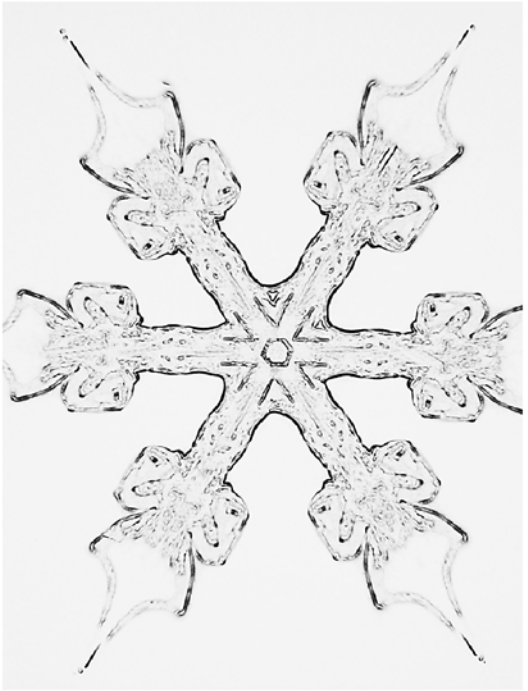


WHEN MOISTURE COALESCES IN THE ATMOSPHERE, IT FORMS A CLOUD. ALTOCUMULUS CLOUDS, WHICH LOOK LIKE OVAL-SHAPED, DENSE, PUFFY BALLS, ARE MIDLEVEL CLOUDS. *(© Mark A. Schneider/Photo Researchers. Reproduced by permission.)*

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.

## WHERE TO LEARN MORE

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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 $1.013 \times 10^5$ 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.

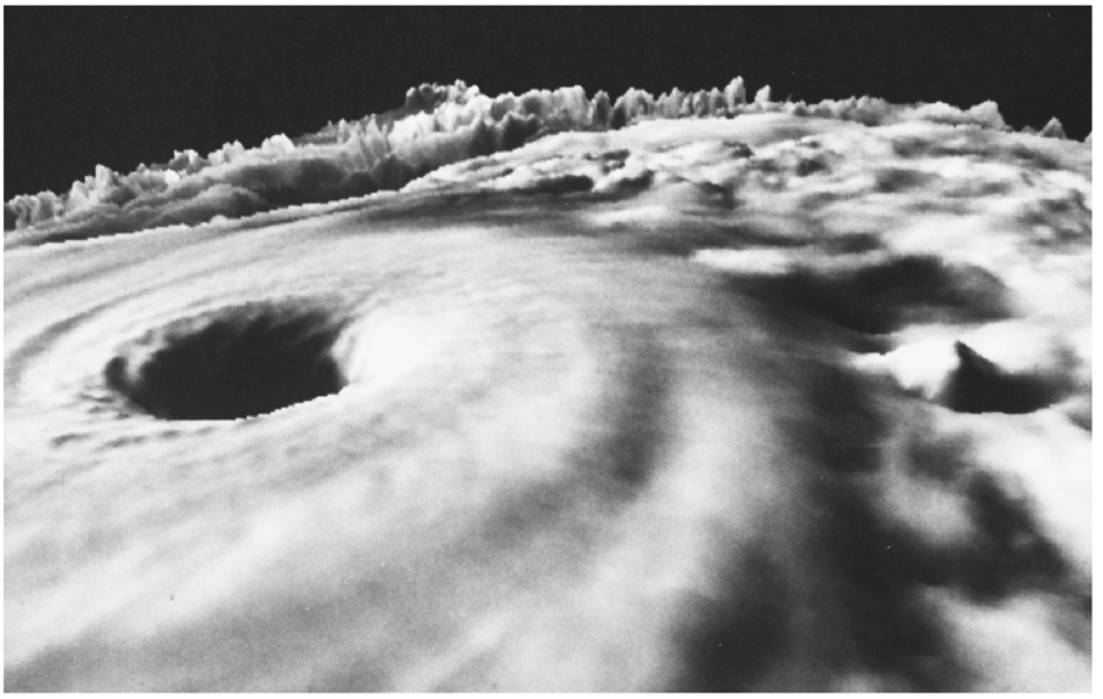
The result was a series of nearly 150 tornadoes, including 48 that were classified as F4 or F5, the highest levels on the Fujita-Pearson scale used to rate the intensity or tornadoes. Some other significant tornado events since that time include the Carolina outbreak, which killed 57 people, injured 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.

## WHERE TO LEARN MORE

*The Atmosphere* (Web site). <http://liftoff.msfc.nasa.gov/academy/space/atmosphere.html>.

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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.*


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*Boldface type indicates main entry volume and page numbers.*
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# SCIENCE OF EVERYDAY THINGS

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## VOLUME 1 REAL-LIFE CHEMISTRY

A Schlager Information Group Book
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Written by Judson Knight

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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 Physics

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 events.
- **Where to Learn More** Includes books, articles, and Internet sites that contain further information about the topic.

Each entry also includes a "Key Terms" section that defines important concepts discussed in the text. Finally, each volume includes numerous illustrations, graphs, tables, and photographs.

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.

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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.

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SCIENCE OF EVERYDAY THINGS

REAL-LIFE CHEMISTRY

# MEASUREMENT

MEASUREMENT

TEMPERATURE AND HEAT

MASS, DENSITY, AND VOLUME

# MEASUREMENT

## CONCEPT

Measurement seems like a simple subject, on the surface at least; indeed, all measurements can be reduced to just two components: number and unit. Yet one might easily ask, "What numbers, and what units?"—a question that helps bring into focus the complexities involved in designating measurements. As it turns out, some forms of numbers are more useful for rendering values than others; hence the importance of significant figures and scientific notation in measurements. The same goes for units. First, one has to determine what is being measured: mass, length, or some other property (such as volume) that is ultimately derived from mass and length. Indeed, the process of learning how to measure reveals not only a fundamental component of chemistry, but an underlying—if arbitrary and manmade—order in the quantifiable world.

## HOW IT WORKS

### Numbers

In modern life, people take for granted the existence of the base-10, of decimal numeration system—a name derived from the Latin word *decem*, meaning "ten." Yet there is nothing obvious about this system, which has its roots in the ten fingers used for basic counting. At other times in history, societies have adopted the two hands or arms of a person as their numerical frame of reference, and from this developed a base-2 system. There have also been base-5 systems relating to the fingers on one hand, and base-20 systems that took as their reference point the combined number of fingers and toes.

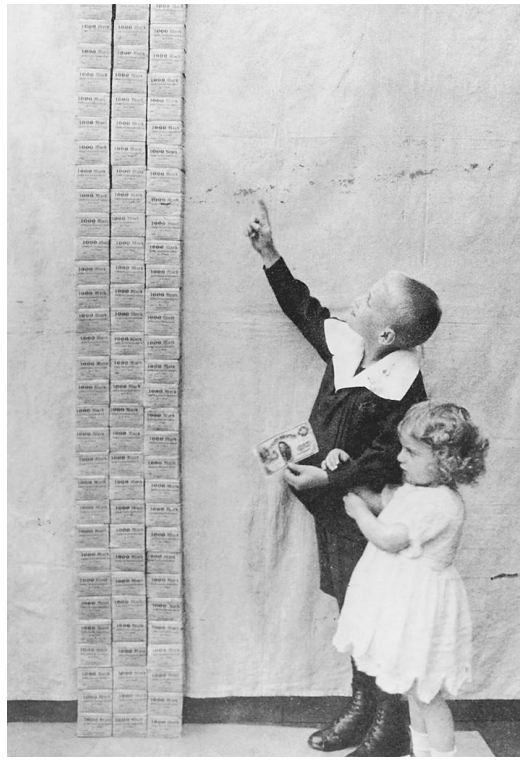
Obviously, there is an arbitrary quality underlying the modern numerical system, yet it works extremely well. In particular, the use of decimal fractions (for example, 0.01 or 0.235) is particularly helpful for rendering figures other than whole numbers. Yet decimal fractions are a relatively recent innovation in Western mathematics, dating only to the sixteenth century. In order to be workable, decimal fractions rely on an even more fundamental concept that was not always part of Western mathematics: place-value.

### Place-Value and Notation Systems

Place-value is the location of a number relative to others in a sequence, a location that makes it possible to determine the number's value. For instance, in the number 347, the 3 is in the hundreds place, which immediately establishes a value for the number in units of 100. Similarly, a person can tell at a glance that there are 4 units of 10, and 7 units of 1.

Of course, today this information appears to be self-evident—so much so that an explanation of it seems tedious and perfunctory—to almost anyone who has completed elementary-school arithmetic. In fact, however, as with almost everything about numbers and units, there is nothing obvious at all about place-value; otherwise, it would not have taken Western mathematicians thousands of years to adopt a place-value numerical system. And though they did eventually make use of such a system, Westerners did not develop it themselves, as we shall see.

**ROMAN NUMERALS.** Numeration systems of various kinds have existed since at least 3000 B.C., but the most important number



Standardization is crucial to maintaining stability in a society. During the German inflationary crisis of the 1920s, hyperinflation led to an economic depression and the rise of Adolf Hitler. Here, two children gaze up at a stack of 100,000 German marks—the equivalent at the time to one U.S. dollar. *(© Bettmann/Corbis.)*

system in the history of Western civilization prior to the late Middle Ages was the one used by the Romans. Rome ruled much of the known world in the period from about 200 B.C. to about A.D. 200, and continued to have an influence on Europe long after the fall of the Western Roman Empire in A.D. 476—an influence felt even today. Though the Roman Empire is long gone and Latin a dead language, the impact of Rome continues: thus, for instance, Latin terms are used to designate species in biology. It is therefore easy to understand how Europeans continued to use the Roman numeral system up until the thirteenth century A.D.—despite the fact that Roman numerals were enormously cumbersome.

The Roman notation system has no means of representing place-value: thus a relatively large number such as 3,000 is shown as MMM, whereas a much smaller number might use many more "places": 438, for instance, is rendered as CDXXXVIII. Performing any sort of calculations with these numbers is a nightmare. Imagine, for instance, trying to multiply these two. With the number system in use today, it is not difficult to multiply 3,000 by 438 in one's head. The problem can be reduced to a few simple steps: multiply 3 by 400, 3 by 30, and 3 by 8; add these products together; then multiply the total by 1,000—a step that requires the placement of three zeroes at the end of the number obtained in the earlier steps.

But try doing this with Roman numerals: it is essentially impossible to perform this calculation without resorting to the much more practical place-value system to which we're accustomed. No wonder, then, that Roman numerals have been relegated to the sidelines, used in modern life for very specific purposes: in outlines, for instance; in ordinal titles (for example, Henry VIII); or in designating the year of a motion picture's release.

**HINDU-ARABIC NUMERALS.** The system of counting used throughout much of the world—1, 2, 3, and so on—is the Hindu-Arabic notation system. Sometimes mistakenly referred to as "Arabic numerals," these are most accurately designated as Hindu or Indian numerals. They came from India, but because Europeans discovered them in the Near East during the Crusades (1095-1291), they assumed the Arabs had invented the notation system, and hence began referring to them as Arabic numerals.

Developed in India during the first millennium B.C., Hindu notation represented a vast improvement over any method in use up to or indeed since that time. Of particular importance was a number invented by Indian mathematicians: zero. Until then, no one had considered zero worth representing since it was, after all, nothing. But clearly the zeroes in a number such as 2,000,002 stand for something. They perform a place-holding function: otherwise, it would be impossible to differentiate between 2,000,002 and 22.

## Uses of Numbers in Science

**SCIENTIFIC NOTATION.** Chemists and other scientists often deal in very large or very small numbers, and if they had to write out these numbers every time they discussed them, their work would soon be encumbered by lengthy numerical expressions. For this purpose, they use scientific notation, a method for writing extremely large or small numbers by representing



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them as a number between 1 and 10 multiplied by a power of 10.

Instead of writing 75,120,000, for instance, the preferred scientific notation is $7.512 \cdot 10^7$. To interpret the value of large multiples of 10, it is helpful to remember that the value of 10 raised to any power n is the same as 1 followed by that number of zeroes. Hence $10^{25}$, for instance, is simply 1 followed by 25 zeroes.

Scientific notation is just as useful—to chemists in particular—for rendering very small numbers. Suppose a sample of a chemical compound weighed 0.0007713 grams. The preferred scientific notation, then, is $7.713 \cdot 10^{-4}$. Note that for numbers less than 1, the power of 10 is a negative number: $10^{-1}$ is 0.1, $10^{-2}$ is 0.01, and so on.

Again, there is an easy rule of thumb for quickly assessing the number of decimal places where scientific notation is used for numbers less than 1. Where 10 is raised to any power –n, the decimal point is followed by n places. If 10 is raised to the power of –8, for instance, we know at a glance that the decimal is followed by 7 zeroes and a 1.

**SIGNIFICANT FIGURES.** In making measurements, there will always be a degree of uncertainty. Of course, when the standards of calibration (discussed below) are very high, and the measuring instrument has been properly calibrated, the degree of uncertainty will be very small. Yet there is bound to be uncertainty to some degree, and for this reason, scientists use significant figures—numbers included in a measurement, using all certain numbers along with the first uncertain number.

Suppose the mass of a chemical sample is measured on a scale known to be accurate to $10^{-5}$ kg. This is equal to 1/100,000 of a kilo, or 1/100 of a gram; or, to put it in terms of place-value, the scale is accurate to the fifth place in a decimal fraction. Suppose, then, that an item is placed on the scale, and a reading of 2.13283697 kg is obtained. All the numbers prior to the 6 are significant figures, because they have been obtained with certainty. On the other hand, the 6 and the numbers that follow are not significant figures because the scale is not known to be accurate beyond $10^{-5}$ kg.

Thus the measure above should be rendered with 7 significant figures: the whole number 2, and the first 6 decimal places. But if the value is given as 2.132836, this might lead to inaccuracies at some point when the measurement is factored into other equations. The 6, in fact, should be "rounded off" to a 7. Simple rules apply to the

rounding off of significant figures: if the digit following the first uncertain number is less than 5, there is no need to round off. Thus, if the measurement had been 2.13283627 kg (note that the 9 was changed to a 2), there is no need to round off, and in this case, the figure of 2.132836 is correct. But since the number following the 6 is in fact a 9, the correct significant figure is 7; thus the total would be 2.132837.

### Fundamental Standards of Measure

So much for numbers; now to the subject of units. But before addressing systems of measurement, what are the properties being measured? All forms of scientific measurement, in fact, can be reduced to expressions of four fundamental properties: length, mass, time, and electric current. Everything can be expressed in terms of these properties: even the speed of an electron spinning around the nucleus of an atom can be shown as "length" (though in this case, the measurement of space is in the form of a circle or even more complex shapes) divided by time.

Of particular interest to the chemist are length and mass: length is a component of volume, and both length and mass are elements of density. For this reason, a separate essay in this book is devoted to the subject of Mass, Density, and Volume. Note that "length," as used in this most basic sense, can refer to distance along any plane, or in any of the three dimensions—commonly known as length, width, and height—of the observable world. (Time is the fourth dimension.) In addition, as noted above, "length" measurements can be circular, in which case the formula for measuring space requires use of the coefficient $\pi$, roughly equal to 3.14.

## REAL-LIFE APPLICATIONS

### Standardized Units of Measure: Who Needs Them?

People use units of measure so frequently in daily life that they hardly think about what they are doing. A motorist goes to the gas station and pumps 13 gallons (a measure of volume) into an automobile. To pay for the gas, the motorist uses dollars—another unit of measure, economic rather than scientific—in the form of paper money, a debit card, or a credit card.

This is simple enough. But what if the motorist did not know how much gas was in a gallon, or if the motorist had some idea of a gallon that differed from what the gas station management determined it to be? And what if the value of a dollar were not established, such that the motorist and the gas station attendant had to haggle over the cost of the gasoline just purchased? The result would be a horribly confused situation: the motorist might run out of gas, or money, or both, and if such confusion were multiplied by millions of motorists and millions of gas stations, society would be on the verge of breakdown.

**THE VALUE OF STANDARDIZATION TO A SOCIETY.** Actually, there have been times when the value of currency was highly unstable, and the result was near anarchy. In Germany during the early 1920s, for instance, rampant inflation had so badly depleted the value of the mark, Germany's currency, that employees demanded to be paid every day so that they could cash their paychecks before the value went down even further. People made jokes about the situation: it was said, for instance, that when a woman went into a store and left a basket containing several million marks out front, thieves ran by and stole the basket—but left the money. Yet there was nothing funny about this situation, and it paved the way for the nightmarish dictatorship of Adolf Hitler and the Nazi Party.

It is understandable, then, that standardization of weights and measures has always been an important function of government. When Ch'in Shih-huang-ti (259-210 B.C.) united China for the first time, becoming its first emperor, he set about standardizing units of measure as a means of providing greater unity to the country—thus making it easier to rule. On the other hand, the Russian Empire of the late nineteenth century failed to adopt standardized systems that would have tied it more closely to the industrialized nations of Western Europe. The width of railroad tracks in Russia was different than in Western Europe, and Russia used the old Julian calendar, as opposed to the Gregorian calendar adopted throughout much of Western Europe after 1582. These and other factors made economic exchanges between Russia and Western Europe

extremely difficult, and the Russian Empire remained cut off from the rapid progress of the West. Like Germany a few decades later, it became ripe for the establishment of a dictatorship—in this case under the Communists led by V. I. Lenin.

Aware of the important role that standardization of weights and measures plays in the governing of a society, the U.S. Congress in 1901 established the Bureau of Standards. Today it is known as the National Institute of Standards and Technology (NIST), a nonregulatory agency within the Commerce Department. As will be discussed at the conclusion of this essay, the NIST maintains a wide variety of standard definitions regarding mass, length, temperature and so forth, against which other devices can be calibrated.

**THE VALUE OF STANDARDIZATION TO SCIENCE.** What if a nurse, rather than carefully measuring a quantity of medicine before administering it to a patient, simply gave the patient an amount that "looked right"? Or what if a pilot, instead of calculating fuel, distance, and other factors carefully before taking off from the runway, merely used a "best estimate"? Obviously, in either case, disastrous results would be likely to follow. Though neither nurses or pilots are considered scientists, both use science in their professions, and those disastrous results serve to highlight the crucial matter of using standardized measurements in science.

Standardized measurements are necessary to a chemist or any scientist because, in order for an experiment to be useful, it must be possible to duplicate the experiment. If the chemist does not know exactly how much of a certain element he or she mixed with another to form a given compound, the results of the experiment are useless. In order to share information and communicate the results of experiments, then, scientists need a standardized "vocabulary" of measures.

This "vocabulary" is the International System of Units, known as SI for its French name, Système International d'Unités. By international agreement, the worldwide scientific community adopted what came to be known as SI at the 9th General Conference on Weights and Measures in 1948. The system was refined at the 11th General Conference in 1960, and given its present name; but in fact most components of SI belong to a much older system of weights and measures developed in France during the late eighteenth century.

## SI vs. the English System

The United States, as almost everyone knows, is the wealthiest and most powerful nation on Earth. On the other hand, Brunei—a tiny nation-state on the island of Java in the Indonesian archipelago—enjoys considerable oil wealth, but is hardly what anyone would describe as a superpower. Yemen, though it is located on the Arabian peninsula, does not even possess significant oil wealth, and is a poor, economically developing nation. Finally, Burma in Southeast Asia can hardly be described even as a "developing" nation: ruled by an extremely repressive military regime, it is one of the poorest nations in the world.

So what do these four have in common? They are the only nations on the planet that have failed to adopt the metric system of weights and measures. The system used in the United States is called the English system, though it should more properly be called the American system, since England itself has joined the rest of the world in "going metric." Meanwhile, Americans continue to think in terms of gallons, miles, and pounds; yet American scientists use the much more convenient metric units that are part of SI.

**HOW THE ENGLISH SYSTEM WORKS (OR DOES NOT WORK).** Like methods of counting described above, most systems of measurement in premodern times were modeled on parts of the human body. The foot is an obvious example of this, while the inch originated from the measure of a king's first thumb joint. At one point, the yard was defined as the distance from the nose of England's King Henry I to the tip of his outstretched middle finger.

Obviously, these are capricious, downright absurd standards on which to base a system of measure. They involve things that change, depending for instance on whose foot is being used as a standard. Yet the English system developed in this willy-nilly fashion over the centuries; today, there are literally hundreds of units—including three types of miles, four kinds of ounces, and five kinds of tons, each with a different value.

What makes the English system particularly cumbersome, however, is its lack of convenient

conversion factors. For length, there are 12 inches in a foot, but 3 feet in a yard, and 1,760 yards in a mile. Where volume is concerned, there are 16 ounces in a pound (assuming one is talking about an avoirdupois ounce), but 2,000 pounds in a ton. And, to further complicate matters, there are all sorts of other units of measure developed to address a particular property: horsepower, for instance, or the British thermal unit (Btu).

**THE CONVENIENCE OF THE METRIC SYSTEM.** Great Britain, though it has long since adopted the metric system, in 1824 established the British Imperial System, aspects of which are reflected in the system still used in America. This is ironic, given the desire of early Americans to distance themselves psychologically from the empire to which their nation had once belonged. In any case, England's great worldwide influence during the nineteenth century brought about widespread adoption of the English or British system in colonies such as Australia and Canada. This acceptance had everything to do with British power and tradition, and nothing to do with convenience. A much more usable standard had actually been embraced 25 years before in a land that was then among England's greatest enemies: France.

During the period leading up to and following the French Revolution of 1789, French intellectuals believed that every aspect of existence could and should be treated in highly rational, scientific terms. Out of these ideas arose much folly, particularly during the Reign of Terror in 1793, but one of the more positive outcomes was the metric system. This system is decimal—that is, based entirely on the number 10 and powers of 10, making it easy to relate one figure to another. For instance, there are 100 centimeters in a meter and 1,000 meters in a kilometer.

**PREFIXES FOR SIZES IN THE METRIC SYSTEM.** For designating smaller values of a given measure, the metric system uses principles much simpler than those of the English system, with its irregular divisions of (for instance) gallons, quarts, pints, and cups. In the metric system, one need only use a simple Greek or Latin prefix to designate that the value is multiplied by a given power of 10. In general, the prefixes for values greater than 1 are Greek, while Latin is used for those less than 1. These prefixes, along with their abbreviations and respective values, are as follows. (The symbol μ for "micro" is the Greek letter mu.)

The Most Commonly Used Prefixes in the Metric System

- giga (G) = $10^9$ (1,000,000,000)
- mega (M) = $10^6$ (1,000,000)
- kilo (k) == $10^3$ (1,000)
- deci (d) = $10^{-1}$ (0.1)
- centi (c) = $10^{-2}$ (0.01)
- milli (m) = $10^{-3}$ (0.001)
- micro (μ) = $10^{-6}$ (0.000001)
- nano (n) = $10^{-9}$ (0.000000001)

The use of these prefixes can be illustrated by reference to the basic metric unit of length, the meter. For long distances, a kilometer (1,000 m) is used; on the other hand, very short distances may require a centimeter (0.01 m) or a millimeter (0.001 m) and so on, down to a nanometer (0.000000001 m). Measurements of length also provide a good example of why SI includes units that are not part of the metric system, though they are convertible to metric units. Hard as it may be to believe, scientists often measure lengths even smaller than a nanometer—the width of an atom, for instance, or the wavelength of a light ray. For this purpose, they use the angstrom (Å or A), equal to 0.1 nanometers.

## Calibration and SI Units

**THE SEVEN BASIC SI UNITS.** The SI uses seven basic units, representing length, mass, time, temperature, amount of substance, electric current, and luminous intensity. The first four parameters are a part of everyday life, whereas the last three are of importance only to scientists. "Amount of substance" is the number of elementary particles in matter. This is measured by the mole, a unit discussed in the essay on Mass, Density, and Volume. Luminous intensity, or the brightness of a light source, is measured in candelas, while the SI unit of electric current is the ampere.

The other four basic units are the meter for length, the kilogram for mass, the second for time, and the degree Celsius for temperature. The last of these is discussed in the essay on Temperature; as for meters, kilograms, and seconds, they will be examined below in terms of the means used to define each.

**CALIBRATION.** Calibration is the process of checking and correcting the performance of a measuring instrument or device against the accepted standard. America's preeminent standard for the exact time of day, for instance, is the United States Naval Observatory in Washington, D.C. Thanks to the Internet, people all over the country can easily check the exact time, and calibrate their clocks accordingly—though, of course, the resulting accuracy is subject to factors such as the speed of the Internet connection.

There are independent scientific laboratories responsible for the calibration of certain instruments ranging from clocks to torque wrenches, and from thermometers to laser-beam power analyzers. In the United States, instruments or devices with high-precision applications—that is, those used in scientific studies, or by high-tech industries—are calibrated according to standards established by the NIST.

The NIST keeps on hand definitions, as opposed to using a meter stick or other physical model. This is in accordance with the methods of calibration accepted today by scientists: rather than use a standard that might vary—for instance, the meter stick could be bent imperceptibly—unvarying standards, based on specific behaviors in nature, are used.

**METERS AND KILOGRAMS.** A meter, equal to 3.281 feet, was at one time defined in terms of Earth's size. Using an imaginary line drawn from the Equator to the North Pole through Paris, this distance was divided into 10 million meters. Later, however, scientists came to the realization that Earth is subject to geological changes, and hence any measurement calibrated to the planet's size could not ultimately be reliable. Today the length of a meter is calibrated according to the amount of time it takes light to travel through that distance in a vacuum (an area of space devoid of air or other matter). The official definition of a meter, then, is the distance traveled by light in the interval of 1/299,792,458 of a second.

One kilogram is, on Earth at least, equal to 2.21 pounds; but whereas the kilogram is a unit of mass, the pound is a unit of weight, so the correspondence between the units varies depending on the gravitational field in which a pound is measured. Yet the kilogram, though it represents a much more fundamental property of the physical world than a pound, is still a somewhat arbitrary form of measure in comparison to the meter as it is defined today.

Given the desire for an unvarying standard against which to calibrate measurements, it would be helpful to find some usable but unchanging standard of mass; unfortunately, scientists have yet to locate such a standard. Therefore, the value of a kilogram is calibrated much as it was two centuries ago. The standard is a bar of platinum-iridium alloy, known as the International Prototype Kilogram, housed near Sèvres in France.

**SECONDS.** A second, of course, is a unit of time as familiar to non-scientifically trained Americans as it is to scientists and people schooled in the metric system. In fact, it has nothing to do with either the metric system or SI. The means of measuring time on Earth are not "metric": Earth revolves around the Sun approximately every 365.25 days, and there is no way to turn this into a multiple of 10 without creating a

## KEY TERMS

**CALIBRATION:** The process of checking and correcting the performance of a measuring instrument or device against a commonly accepted standard.

**SCIENTIFIC NOTATION:** A method used by scientists for writing extremely large or small numbers by representing them as a number between 1 and 10 multiplied by a power of 10. Instead of writing 0.0007713, the preferred scientific notation is $7.713 \cdot 10^{-4}$.

**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.

**SIGNIFICANT FIGURES:** Numbers included in a measurement, using all certain numbers along with the first uncertain number.

situation even more cumbersome than the English units of measure.

The week and the month are units based on cycles of the Moon, though they are no longer related to lunar cycles because a lunar year would soon become out-of-phase with a year based on Earth's rotation around the Sun. The continuing use of weeks and months as units of time is based on tradition—as well as the essential need of a society to divide up a year in some way.

A day, of course, is based on Earth's rotation, but the units into which the day is divided—hours, minutes, and seconds—are purely arbitrary, and likewise based on traditions of long standing. Yet scientists must have some unit of time to use as a standard, and, for this purpose, the second was chosen as the most practical. The SI definition of a second, however, is not simply one-sixtieth of a minute or anything else so strongly influenced by the variation of Earth's movement.

Instead, the scientific community chose as its standard the atomic vibration of a particular isotope of the metal cesium, cesium-133. The vibration of this atom is presumed to be unvarying, because the properties of elements—unlike the size of Earth or its movement—do not change. Today, a second is defined as the amount of time it takes for a cesium-133 atom to vibrate 9,192,631,770 times. Expressed in scientific notation, with significant figures, this is $9.19263177 \cdot 10^9$.

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# TEMPERATURE AND HEAT

## CONCEPT

Temperature, heat, and related concepts belong to the world of physics rather than chemistry; yet it would be impossible for the chemist to work without an understanding of these properties. Thermometers, of course, measure temperature according to one or both of two well-known scales based on the freezing and boiling points of water, though scientists prefer a scale based on the virtual freezing point of all matter. Also related to temperature are specific heat capacity, or the amount of energy required to change the temperature of a substance, and also calorimetry, the measurement of changes in heat as a result of physical or chemical changes. Although these concepts do not originate from chemistry but from physics, they are no less useful to the chemist.

## HOW IT WORKS

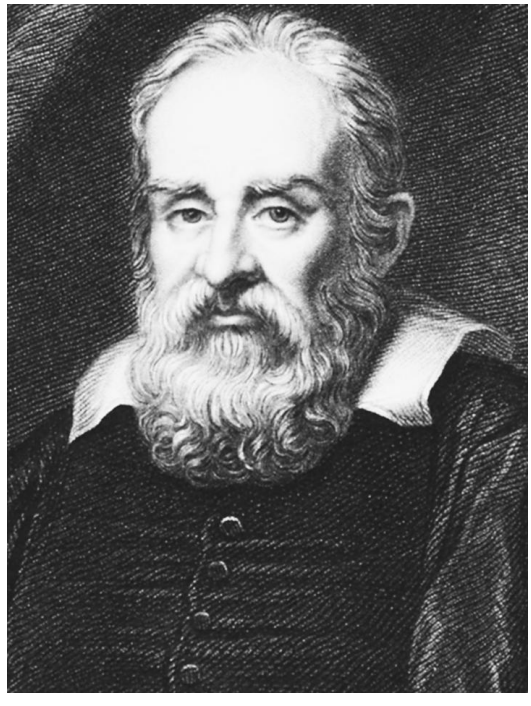
### Energy

The area of physics known as thermodynamics, discussed briefly below in terms of thermodynamics laws, is the study of the relationships between heat, work, and energy. Work is defined as the exertion of force over a given distance to displace or move an object, and energy is the ability to accomplish work. Energy appears in numerous manifestations, including thermal energy, or the energy associated with heat.

Another type of energy—one of particular interest to chemists—is chemical energy, related to the forces that attract atoms to one another in chemical bonds. Hydrogen and oxygen atoms in water, for instance, are joined by chemical bonding, and when those bonds are broken, the forces joining the atoms are released in the form of chemical energy. Another example of chemical energy release is combustion, whereby chemical bonds in fuel, as well as in oxygen molecules, are broken and new chemical bonds are formed. The total energy in the newly formed chemical bonds is less than the energy of the original bonds, but the energy that makes up the difference is not lost; it has simply been released.

Energy, in fact, is never lost: a fundamental law of the universe is the conservation of energy, which states that in a system isolated from all other outside factors, the total amount of energy remains the same, though transformations of energy from one form to another take place. When a fire burns, then, some chemical energy is turned into thermal energy. Similar transformations occur between these and other manifestations of energy, including electrical and magnetic (sometimes these two are combined as electromagnetic energy), sound, and nuclear energy. If a chemical reaction makes a noise, for instance, some of the energy in the substances being mixed has been dissipated to make that sound. The overall energy that existed before the reaction will be the same as before; however, the energy will not necessarily be in the same place as before.

Note that chemical and other forms of energy are described as "manifestations," rather than "types," of energy. In fact, all of these can be described in terms of two basic types of energy: kinetic energy, or the energy associated with movement, and potential energy, or the energy associated with position. The two are inversely related: thus, if a spring is pulled back to its maximum point of tension, its potential energy is



During his lifetime, Galileo constructed a thermoscope, the first practical temperature-measuring device. *(Archive Photos, Inc. Reproduced by permission.)*

also at a maximum, while its kinetic energy is zero. Once it is released and begins springing through the air to return to the position it maintained before it was stretched, it begins gaining kinetic energy and losing potential energy.

## Heat

Thermal energy is actually a form of kinetic energy generated by the movement of particles at the atomic or molecular level: the greater the movement of these particles, the greater the thermal energy. When people use the word "heat" in ordinary language, what they are really referring to is "the quality of hotness"—that is, the thermal energy internal to a system. In scientific terms, however, heat is internal thermal energy that flows from one body of matter to another—or, more specifically, from a system at a higher temperature to one at a lower temperature.

Two systems at the same temperature are said to be in a state of thermal equilibrium. When this state exists, there is no exchange of heat. Though in everyday terms people speak of "heat" as an expression of relative warmth or coldness, in scientific terms, heat exists only in transfer between two systems. Furthermore, there can never be a transfer of "cold"; although coldness is a recognizable sensory experience in human life, in scientific terms, cold is simply the absence of heat.

If you grasp a snowball in your hand, the hand of course gets cold. The mind perceives this as a transfer of cold from the snowball, but in fact exactly the opposite has happened: heat has moved from your hand to the snow, and if enough heat enters the snowball, it will melt. At the same time, the departure of heat from your hand results in a loss of internal energy near the surface of the hand, experienced as a sensation of coldness.

## Understanding Temperature

Just as heat does not mean the same thing in scientific terms as it does in ordinary language, so "temperature" requires a definition that sets it apart from its everyday meaning. Temperature may be defined as a measure of the average internal energy in a system. Two systems in a state of thermal equilibrium have the same temperature; on the other hand, differences in temperature determine the direction of internal energy flow between two systems where heat is being transferred.

This can be illustrated through an experience familiar to everyone: having one's temperature taken with a thermometer. If one has a fever, the mouth will be warmer than the thermometer, and therefore heat will be transferred to the thermometer from the mouth. The thermometer, discussed in more depth later in this essay, measures the temperature difference between itself and any object with which it is in contact.

## Temperature and Thermodynamics

One might pour a kettle of boiling water into a cold bathtub to heat it up; or one might put an ice cube in a hot cup of coffee "to cool it down." In everyday experience, these seem like two very different events, but from the standpoint of thermodynamics, they are exactly the same. In both cases, a body of high temperature is placed in contact with a body of low temperature, and in both cases, heat passes from the high-temperature body to the low-temperature body.

The boiling water warms the tub of cool water, and due to the high ratio of cool water to boiling water in the bathtub, the boiling water



Because of water's high specific heat capacity, cities located next to large bodies of water tend to stay warmer in the winter and cooler in the summer. During the early summer months, for instance, Chicago's lakefront stays cooler than areas further inland. This is because the lake is cooled from the winter's cold temperatures and snow runoff. *(Farrell Grehan/Corbis. Reproduced by permission.)*

expends all its energy raising the temperature in the bathtub as a whole. The greater the ratio of very hot water to cool water, of course, the warmer the bathtub will be in the end. But even after the bath water is heated, it will continue to lose heat, assuming the air in the room is not warmer than the water in the tub—a safe assumption. If the water in the tub is warmer than the air, it will immediately begin transferring thermal energy to the lower-temperature air until their temperatures are equalized.

As for the coffee and the ice cube, what happens is opposite to the explanation ordinarily given. The ice does not "cool down" the coffee: the coffee warms up, and presumably melts, the ice. However, it expends at least some of its thermal energy in doing so, and, as a result, the coffee becomes cooler than it was.

**THE LAWS OF THERMODYNAMICS.** These situations illustrate the second of the three laws of thermodynamics. Not only do these laws help to clarify the relationship between heat, temperature, and energy, but they also set limits on what can be accomplished in the world. Hence British writer and scientist C. P. Snow (1905-1980) once described the thermodynamics laws as a set of rules governing an impossible game.

The first law of thermodynamics is essentially the same as the conservation of energy: 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. It could be said that the conservation of energy shows that "the glass is half full": energy is never lost. By contrast, the first law of thermodynamics shows that "the glass is half empty": no system can ever produce more energy than was put into it. Snow therefore summed up the first law as stating that the game is impossible to win.

The second law of thermodynamics begins from the fact that the natural flow of heat is always from an area of higher temperature to an area of lower temperature—just as was shown in the bathtub and coffee cup examples above. Consequently, it is impossible for any system to take heat from a source and perform an equivalent amount of work: some of the heat will always be lost. In other words, no system can ever be perfectly efficient: there will always be a degree of

breakdown, evidence of a natural tendency called entropy.

Snow summed up the second law of thermodynamics, sometimes called "the law of entropy," thus: not only is it impossible to win, it is impossible to break even. In effect, the second law compounds the "bad news" delivered by the first with some even worse news. Though it is true that energy is never lost, the energy available for work output will never be as great as the energy put into a system.

The third law of thermodynamics states that at the temperature of absolute zero—a phenomenon discussed later in this essay—entropy also approaches zero. This might seem to counteract the second law, but in fact the third states in effect that absolute zero is impossible to reach. The French physicist and engineer Sadi Carnot (1796-1832) had shown that a perfectly efficient engine is one whose lowest temperature was absolute zero; but the second law of thermodynamics shows that a perfectly efficient engine (or any other perfect system) cannot exist. Hence, as Snow observed, not only is it impossible to win or break even; it is impossible to get out of the game.

## REAL-LIFE APPLICATIONS

### Evolution of the Thermometer

A thermometer is a device that gauges temperature by measuring a temperature-dependent property, such as the expansion of a liquid in a sealed tube. The Greco-Roman physician Galen (c. 129-c. 199) was among the first thinkers to envision a scale for measuring temperature, but development of a practical temperature-measuring device—the thermoscope—did not occur until the sixteenth century.

The great physicist Galileo Galilei (1564-1642) may have invented the thermoscope; certainly he constructed one. Galileo's thermoscope consisted of a long glass tube planted in a container of liquid. Prior to inserting the tube into the liquid—which was usually colored water, though Galileo's thermoscope used wine—as much air as possible was removed from the tube. This created a vacuum (an area devoid of matter, including air), and as a result of pressure differences between the liquid and the interior of the thermoscope tube, some of the liquid went into the tube.

But the liquid was not the thermometric medium—that is, the substance whose temperature-dependent property changes were measured by the thermoscope. (Mercury, for instance, is the thermometric medium in many thermometers today; however, due to the toxic quality of mercury, an effort is underway to remove mercury thermometers from U.S. schools.) Instead, the air was the medium whose changes the thermoscope measured: when it was warm, the air expanded, pushing down on the liquid; and when the air cooled, it contracted, allowing the liquid to rise.

**EARLY THERMOMETERS: THE SEARCH FOR A TEMPERATURE SCALE.** The first true thermometer, built by Ferdinand II, Grand Duke of Tuscany (1610-1670) in 1641, used alcohol sealed in glass. The latter was marked with a temperature scale containing 50 units, but did not designate a value for zero. In 1664, English physicist Robert Hooke (1635-1703) created a thermometer with a scale divided into units equal to about 1/500 of the volume of the thermometric medium. For the zero point, Hooke chose the temperature at which water freezes, thus establishing a standard still used today in the Fahrenheit and Celsius scales.

Olaus Roemer (1644-1710), a Danish astronomer, introduced another important standard. Roemer's thermometer, built in 1702, was based not on one but two fixed points, which he designated as the temperature of snow or crushed ice on the one hand, and the boiling point of water on the other. As with Hooke's use of the freezing point, Roemer's idea of designating the freezing and boiling points of water as the two parameters for temperature measurements has remained in use ever since.

### Temperature Scales

**THE FAHRENHEIT SCALE.** Not only did he develop the Fahrenheit scale, oldest of the temperature scales still used in Western nations today, but in 1714, German physicist Daniel Fahrenheit (1686-1736) built the first thermometer to contain mercury as a thermometric medium. Alcohol has a low boiling point, whereas mercury remains fluid at a wide range of temperatures. In addition, it expands and con-

tracts at a very constant rate, and tends not to stick to glass. Furthermore, its silvery color makes a mercury thermometer easy to read.

Fahrenheit also conceived the idea of using "degrees" to measure temperature. It is no mistake that the same word refers to portions of a circle, or that exactly 180 degrees—half the number of degrees in a circle—separate the freezing and boiling points for water on Fahrenheit's thermometer. Ancient astronomers first divided a circle into 360 degrees, as a close approximation of the ratio between days and years, because 360 has a large quantity of divisors. So, too, does 180—a total of 16 whole-number divisors other than 1 and itself.

Though today it might seem obvious that 0 should denote the freezing point of water, and 180 its boiling point, such an idea was far from obvious in the early eighteenth century. Fahrenheit considered a 0-to-180 scale, but also a 180-to-360 one, yet in the end he chose neither—or rather, he chose not to equate the freezing point of water with zero on his scale. For zero, he chose the coldest possible temperature he could create in his laboratory, using what he described as "a mixture of sal ammoniac or sea salt, ice, and water." Salt lowers the melting point of ice (which is why it is used in the northern United States to melt snow and ice from the streets on cold winter days), and thus the mixture of salt and ice produced an extremely cold liquid water whose temperature he equated to zero.

On the Fahrenheit scale, the ordinary freezing point of water is 32°, and the boiling point exactly 180° above it, at 212°. Just a few years after Fahrenheit introduced his scale, in 1730, a French naturalist and physicist named Rene Antoine Ferchault de Reaumur (1683-1757) presented a scale for which 0° represented the freezing point of water and 80° the boiling point. Although the Reaumur scale never caught on to the same extent as Fahrenheit's, it did include one valuable addition: the specification that temperature values be determined at standard sea-level atmospheric pressure.

**THE CELSIUS SCALE.** With its 32° freezing point and its 212° boiling point, the Fahrenheit system lacks the neat orderliness of a decimal or base-10 scale. Thus when France adopted the metric system in 1799, it chose as its temperature scale not the Fahrenheit but the Celsius scale. The latter was created in 1742 by Swedish astronomer Anders Celsius (1701-1744).

Like Fahrenheit, Celsius chose the freezing and boiling points of water as his two reference points, but he determined to set them 100, rather than 180, degrees apart. The Celsius scale is sometimes called the centigrade scale, because it is divided into 100 degrees, cent being a Latin root meaning "hundred." Interestingly, Celsius planned to equate 0° with the boiling point, and 100° with the freezing point; only in 1750 did fellow Swedish physicist Martin Strömer change the orientation of the Celsius scale. In accordance with the innovation offered by Reaumur, Celsius's scale was based not simply on the boiling and freezing points of water, but specifically on those points at normal sea-level atmospheric pressure.

In SI, a scientific system of measurement that incorporates units from the metric system along with additional standards used only by scientists, the Celsius scale has been redefined in terms of the triple point of water. (Triple point is the temperature and pressure at which a substance is at once a solid, liquid, and vapor.) According to the SI definition, the triple point of water—which occurs at a pressure considerably below normal atmospheric pressure—is exactly 0.01°C.

**THE KELVIN SCALE.** French physicist and chemist J. A. C. Charles (1746-1823), who is credited with the gas law that bears his name (see below), discovered that at 0°C, the volume of gas at constant pressure drops by 1/273 for every Celsius degree drop in temperature. This suggested that the gas would simply disappear if cooled to -273°C, which of course made no sense.

The man who solved the quandary raised by Charles's discovery was William Thompson, Lord Kelvin (1824-1907), who, in 1848, put forward the suggestion that it was the motion of molecules, and not volume, that would become zero at –273°C. He went on to establish what came to be known as the Kelvin scale. Sometimes known as the absolute temperature scale, the Kelvin scale is based not on the freezing point of water, but on absolute zero—the temperature at which molecular motion comes to a virtual stop. This is –273.15°C (–459.67°F), which, in the Kelvin scale, is designated as 0K. (Kelvin measures do not use the term or symbol for "degree.")

Though scientists normally use metric units, they prefer the Kelvin scale to Celsius because the absolute temperature scale is directly related to average molecular translational energy, based on the relative motion of molecules. Thus if the Kelvin temperature of an object is doubled, this means its average molecular translational energy has doubled as well. The same cannot be said if the temperature were doubled from, say, 10°C to 20°C, or from 40°C to 80°F, since neither the Celsius nor the Fahrenheit scale is based on absolute zero.

**CONVERSIONS BETWEEN SCALES.** The Kelvin scale is closely related to the Celsius scale, in that a difference of one degree measures the same amount of temperature in both. Therefore, Celsius temperatures can be converted to Kelvins by adding 273.15. Conversion between Celsius and Fahrenheit figures, on the other hand, is a bit trickier.

To convert a temperature from Celsius to Fahrenheit, multiply by 9/5 and add 32. It is important to perform the steps in that order, because reversing them will produce a wrong figure. Thus, 100°C multiplied by 9/5 or 1.8 equals 180, which, when added to 32 equals 212°F. Obviously, this is correct, since 100°C and 212°F each represent the boiling point of water. But if one adds 32 to 100°, then multiplies it by 9/5, the result is 237.6°F—an incorrect answer.

For converting Fahrenheit temperatures to Celsius, there are also two steps involving multiplication and subtraction, but the order is reversed. Here, the subtraction step is performed before the multiplication step: thus 32 is subtracted from the Fahrenheit temperature, then the result is multiplied by 5/9. Beginning with 212°F, when 32 is subtracted, this equals 180. Multiplied by 5/9, the result is 100°C—the correct answer.

One reason the conversion formulae use simple fractions instead of decimal fractions (what most people simply call "decimals") is that 5/9 is a repeating decimal fraction (0.55555....) Furthermore, the symmetry of 5/9 and 9/5 makes memorization easy. One way to remember the formula is that Fahrenheit is multiplied by a fraction—since 5/9 is a real fraction, whereas 9/5 is actually a mixed number, or a whole number plus a fraction.

## Modern Thermometers

**MERCURY THERMOMETERS.** For a thermometer, it is important that the glass tube be kept sealed; changes in atmospheric pressure contribute to inaccurate readings, because they influence the movement of the thermometric medium. It is also important to have a reliable thermometric medium, and, for this reason, water—so useful in many other contexts—was quickly discarded as an option.

Water has a number of unusual properties: it does not expand uniformly with a rise in temperature, or contract uniformly with a lowered temperature. Rather, it reaches its maximum density at 39.2°F (4°C), and is less dense both above and below that temperature. Therefore alcohol, which responds in a much more uniform fashion to changes in temperature, soon took the place of water, and is still used in many thermometers today. But for the reasons mentioned earlier, mercury is generally considered preferable to alcohol as a thermometric medium.

In a typical mercury thermometer, mercury is placed in a long, narrow sealed tube called a capillary. The capillary is inscribed with figures for a calibrated scale, usually in such a way as to allow easy conversions between Fahrenheit and Celsius. A thermometer is calibrated by measuring the difference in height between mercury at the freezing point of water, and mercury at the boiling point of water. The interval between these two points is then divided into equal increments—180, as we have seen, for the Fahrenheit scale, and 100 for the Celsius scale.

**VOLUME GAS THERMOMETERS.** Whereas most liquids and solids expand at an irregular rate, gases tend to follow a fairly regular pattern of expansion in response to increases in temperature. The predictable behavior of gases in these situations has led to the development of the volume gas thermometer, a highly reliable instrument against which other thermometers—including those containing mercury—are often calibrated.

In a volume gas thermometer, an empty container is attached to a glass tube containing mercury. As gas is released into the empty container; this causes the column of mercury to move upward. The difference between the earlier position of the mercury and its position after the introduction of the gas shows the difference between normal atmospheric pressure and the

pressure of the gas in the container. It is then possible to use the changes in the volume of the gas as a measure of temperature.

**ELECTRIC THERMOMETERS.** All matter displays a certain resistance to electric current, a resistance that changes with temperature; because of this, it is possible to obtain temperature measurements using an electric thermometer. A resistance thermometer is equipped with a fine wire wrapped around an insulator: when a change in temperature occurs, the resistance in the wire changes as well. This allows much quicker temperature readings than those offered by a thermometer containing a traditional thermometric medium.

Resistance thermometers are highly reliable, but expensive, and primarily are used for very precise measurements. More practical for everyday use is a thermistor, which also uses the principle of electric resistance, but is much simpler and less expensive. Thermistors are used for providing measurements of the internal temperature of food, for instance, and for measuring human body temperature.

Another electric temperature-measurement device is a thermocouple. When wires of two different materials are connected, this creates a small level of voltage that varies as a function of temperature. A typical thermocouple uses two junctions: a reference junction, kept at some constant temperature, and a measurement junction. The measurement junction is applied to the item whose temperature is to be measured, and any temperature difference between it and the reference junction registers as a voltage change, measured with a meter connected to the system.

**OTHER TYPES OF THERMOMETER.** A pyrometer also uses electromagnetic properties, but of a very different kind. Rather than responding to changes in current or voltage, the pyrometer is gauged to respond to visible and infrared radiation. As with the thermocouple, a pyrometer has both a reference element and a measurement element, which compares light readings between the reference filament and the object whose temperature is being measured.

Still other thermometers, such as those in an oven that register the oven's internal temperature, are based on the expansion of metals with heat. In fact, there are a wide variety of thermometers, each suited to a specific purpose. A pyrometer, for instance, is good for measuring the temperature of a object with which the thermometer itself is not in physical contact.

## Measuring Heat

The measurement of temperature by degrees in the Fahrenheit or Celsius scales is a part of daily life, but measurements of heat are not as familiar to the average person. Because heat is a form of energy, and energy is the ability to perform work, heat is therefore measured by the same units as work. The principal SI unit of work or energy is the joule (J). A joule is equal to 1 newton-meter (N • m)—in other words, the amount of energy required to accelerate a mass of 1 kilogram at the rate of 1 meter per second squared across a distance of 1 meter.

The joule's equivalent in the English system is the foot-pound: 1 foot-pound is equal to 1.356 J, and 1 joule is equal to 0.7376 ft • lbs. In the British system, Btu, or British thermal unit, is another measure of energy, though it is primarily used for machines. Due to the cumbersome nature of the English system, contrasted with the convenience of the decimal units in the SI system, these English units of measure are not used by chemists or other scientists for heat measurement.

## Specific Heat Capacity

Specific heat capacity (sometimes called specific heat) 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 1°C. Typically, specific heat capacity is measured in units of J/g • °C (joules per gram-degree Celsius).

The specific heat capacity of water is measured by the calorie, which, along with the joule, is an important SI measure of heat. Often another unit, the kilocalorie—which, as its name suggests—is 1,000 calories—is used. This is one of the few confusing aspects of SI, which is much simpler than the English system. The dietary Calorie (capital C) with which most people are familiar is not the same as a calorie (lowercase c)—rather, a dietary Calorie is the same as a kilocalorie.

**COMPARING SPECIFIC HEAT CAPACITIES.** The higher the specific heat capacity, the more resistant the substance is to changes in temperature. Many metals, in fact, have a low specific heat capacity, making them easy to heat up and cool down. This contributes

to the tendency of metals to expand when heated, and thus affects their malleability. On the other hand, water has a high specific heat capacity, as discussed below; indeed, if it did not, life on Earth would hardly be possible.

One of the many unique properties of water is its very high specific heat capacity, which is easily derived from the value of a kilocalorie: it is 4.184, the same number of joules required to equal a calorie. Few substances even come close to this figure. At the low end of the spectrum are lead, gold, and mercury, with specific heat capacities of 0.13, 0.13, and 0.14 respectively. Aluminum has a specific heat capacity of 0.89, and ethyl alcohol of 2.43. The value for concrete, one of the highest for any substance other than water, is 2.9.

As high as the specific heat capacity of concrete is, that of water is more than 40% higher. On the other hand, water in its vapor state (steam) has a much lower specific heat capacity—2.01. The same is true for solid water, or ice, with a specific heat capacity of 2.03. Nonetheless, water in its most familiar form has an astoundingly high specific heat capacity, and this has several effects in the real world.

**Effects of water's high specific heat capacity.** For instance, water is much slower to freeze in the winter than most substances. Furthermore, due to other unusual aspects of water—primarily the fact that it actually becomes less dense as a solid—the top of a lake or other body of water freezes first. Because ice is a poor medium for the conduction of heat (a consequence of its specific heat capacity), the ice at the top forms a layer that protects the still-liquid water below it from losing heat. As a result, the water below the ice layer does not freeze, and the animal and plant life in the lake is preserved.

Conversely, when the weather is hot, water is slow to experience a rise in temperature. For this reason, a lake or swimming pool makes a good place to cool off on a sizzling summer day. Given the high specific heat capacity of water, combined with the fact that much of Earth's surface is composed of water, the planet is far less susceptible than other bodies in the Solar System to variations in temperature.

The same is true of another significant natural feature, one made mostly of water: the human body. A healthy human temperature is 98.6°F (37°C), and, even in cases of extremely high fever, an adult's temperature rarely climbs by more than 5°F (2.7°C). The specific heat capacity of the human body, though it is of course lower than that of water itself (since it is not entirely made of water), is nonetheless quite high: 3.47.

## Calorimetry

The measurement of heat gain or loss as a result of physical or chemical change is called calorimetry (pronounced kal-or-IM-uh-tree). Like the word "calorie," the term is derived from a Latin root word meaning "heat." The foundations of calorimetry go back to the mid-nineteenth century, but the field owes much to the work of scientists about 75 years prior to that time.

In 1780, French chemist Antoine Lavoisier (1743-1794) and French astronomer and mathematician Pierre Simon Laplace (1749-1827) had used a rudimentary ice calorimeter for measuring heat in the formations of compounds. Around the same time, Scottish chemist Joseph Black (1728-1799) became the first scientist to make a clear distinction between heat and temperature.

By the mid-1800s, a number of thinkers had come to the realization that—contrary to prevailing theories of the day—heat was a form of energy, not a type of material substance. (The belief that heat was a material substance, called "phlogiston," and that phlogiston was the part of a substance that burned in combustion, had originated in the seventeenth century. Lavoisier was the first scientist to successfully challenge the phlogiston theory.) Among these were American-British physicist Benjamin Thompson, Count Rumford (1753-1814) and English chemist James Joule (1818-1889)—for whom, of course, the joule is named.

Calorimetry as a scientific field of study actually had its beginnings with the work of French chemist Pierre-Eugene Marcelin Berthelot (1827-1907). During the mid-1860s, Berthelot became intrigued with the idea of measuring heat, and, by 1880, he had constructed the first real calorimeter.

**Calorimeters.** Essential to calorimetry is the calorimeter, which can be any device for accurately measuring the temperature of a substance before and after a change occurs. A calorimeter can be as simple as a styrofoam cup. Its quality as an insulator, which makes styro-

foam ideal both for holding in the warmth of coffee and protecting the human hand from scalding, also makes styrofoam an excellent material for calorimetric testing. With a styrofoam calorimeter, the temperature of the substance inside the cup is measured, a reaction is allowed to take place, and afterward, the temperature is measured a second time.

The most common type of calorimeter used is the bomb calorimeter, designed to measure the heat of combustion. Typically, a bomb calorimeter consists of a large container filled with water, into which is placed a smaller container, the combustion crucible. The crucible is made of metal, with thick walls into which is cut an opening to allow the introduction of oxygen. In addition, the combustion crucible is designed to be connected to a source of electricity.

In conducting a calorimetric test using a bomb calorimeter, the substance or object to be studied is placed inside the combustion crucible and ignited. The resulting reaction usually occurs so quickly that it resembles the explosion of a bomb—hence the name "bomb calorimeter." Once the "bomb" goes off, the resulting transfer of heat creates a temperature change in the water, which can be readily gauged with a thermometer.

To study heat changes at temperatures higher than the boiling point of water, physicists use substances with higher boiling points. For experiments involving extremely large temperature ranges, an aneroid (without liquid) calorimeter may be used. In this case, the lining of the combustion crucible must be of a metal, such as copper, with a high coefficient or factor of thermal conductivity—that is, the ability to conduct heat from molecule to molecule.

## Temperature in Chemistry

**THE GAS LAWS.** A collection of statements regarding the behavior of gases, the gas laws are so important to chemistry that a separate essay is devoted to them elsewhere. Several of the gas laws relate temperature to pressure and volume for gases. Indeed, gases respond to changes in temperature with dramatic changes in volume; hence the term "volume," when used in reference to a gas, is meaningless unless pressure and temperature are specified as well.

Among the gas laws, Boyle's law holds that in conditions of constant temperature, an inverse relationship exists between the volume and pressure of a gas: the greater the pressure, the less the volume, and vice versa. Even more relevant to the subject of thermal expansion is Charles's law, which states that when pressure is kept constant, there is a direct relationship between volume and absolute temperature.

**CHEMICAL EQUILIBRIUM AND CHANGES IN TEMPERATURE.** Just as two systems that exchange no heat are said to be in a state of thermal equilibrium, chemical equilibrium describes a dynamic state in which the concentration of reactants and products remains constant. Though the concentrations of reactants and products do not change, note that chemical equilibrium is a dynamic state—in other words, there is still considerable molecular activity, but no net change.

Calculations involving chemical equilibrium make use of a figure called the equilibrium constant (K). According to Le Châtelier's principle, named after French chemist Henri Le Châtelier (1850-1936), whenever a stress or change is imposed on a chemical system in equilibrium, the system will adjust the amounts of the various substances in such a way as to reduce the impact of that stress. An example of a stress is a change in temperature, which changes the equilibrium equation by shifting K (itself dependant on temperature).

Using Le Châtelier's law, it is possible to determine whether K will change in the direction of the forward or reverse reaction. In an exothermic reaction (a reaction that produces heat), K will shift to the left, or in the direction of the forward reaction. On the other hand, in an endothermic reaction (a reaction that absorbs heat), K will shift to the right, or in the direction of the reverse reaction.

**TEMPERATURE AND REACTION RATES.** Another important function of temperature in chemical processes is its function of speeding up chemical reactions. An increase in the concentration of reacting molecules, naturally, leads to a sped-up reaction, because there are simply more molecules colliding with one another. But it is also possible to speed up the reaction without changing the concentration.

By definition, wherever a temperature increase is involved, there is always an increase in average molecular translational energy. When temperatures are high, more molecules are col-

## KEY TERMS

**ABSOLUTE ZERO:** The temperature, defined as 0K on the Kelvin scale, at which the motion of molecules in a solid virtually ceases. The third law of thermodynamics establishes the impossibility of actually reaching absolute zero.

**CALORIE:** A measure of specific heat capacity in the SI or metric system, equal to the heat that must be added to or removed from 1 gram of water to change its temperature by 1°C. The dietary Calorie (capital C), with which most people are familiar, is the same as the kilocalorie.

**CALORIMETRY:** The measurement of heat gain or loss as a result of physical or chemical change.

**CELSIUS SCALE:** The metric scale of temperature, sometimes known as the centigrade scale, created in 1742 by Swedish astronomer Anders Celsius (1701-1744). The Celsius scale establishes the freezing and boiling points of water at 0° and 100° respectively. To convert a temperature from the Celsius to the Fahrenheit scale, multiply by 9/5 and add 32. Though the worldwide scientific community uses the metric or SI system for most measurements, scientists prefer the related Kelvin scale of absolute temperature.

**CONSERVATION OF ENERGY:** A law of physics which holds that within a system isolated from all other 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.

**ENERGY:** The ability to accomplish work—that is, the exertion of force over a given distance to displace or move an object.

**ENTROPY:** The tendency of natural systems toward breakdown, and specifically the tendency for the energy in a system to be dissipated. Entropy is closely related to the second law of thermodynamics.

**FAHRENHEIT SCALE:** The oldest of the temperature scales still in use, created in 1714 by German physicist Daniel Fahrenheit (1686-1736). The Fahrenheit scale establishes the freezing and boiling points of water at 32° and 212° respectively. To convert a temperature from the Fahrenheit to the Celsius scale, subtract 32 and multiply by 5/9.

**FIRST LAW OF THERMODYNAMICS:** A law which states 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.

**HEAT:** Internal thermal energy that flows from one body of matter to another.

**JOULE:** The principal unit of energy—and thus of heat—in the SI or metric system, corresponding to 1 newton-meter (N • m). A joule (J) is equal to 0.7376 foot-pounds in the English system.

**KELVIN SCALE:** Established by William Thompson, Lord Kelvin (1824-1907), the Kelvin scale measures temperature in relation to absolute zero, or 0K. (Units in the Kelvin system, known as Kelvins, do not include the word or symbol

## KEY TERMS CONTINUED

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 Kelvins by adding 273.15.

**KILOCALORIE:** A measure of specific heat capacity in the SI or metric system, equal to the heat that must be added to or removed from 1 kilogram of water to change its temperature by 1°C. As its name suggests, a kilocalorie is 1,000 calories. The dietary Calorie (capital C) with which most people are familiar is the same as the kilocalorie.

**KINETIC ENERGY:** The energy that an object possesses by virtue of its motion.

**MOLECULAR TRANSLATIONAL ENERGY:** The kinetic energy in a system produced by the movement of molecules in relation to one another. Thermal energy is a manifestation of molecular translational energy.

**SECOND LAW OF THERMODYNAMICS:** A law of thermodynamics which states that no system can simply take heat from a source and perform an equivalent amount of work. This is a result of the fact that the natural flow of heat is always from a high-temperature reservoir to a low-temperature reservoir. In the course of such a transfer, some of the heat will always be lost—an example of entropy. The second law is sometimes referred to as "the law of entropy."

**SPECIFIC HEAT CAPACITY:** The amount of heat that must be added to, or removed from, a unit of mass of a given substance to change its temperature by 1°C. It is typically measured in J/g • °C (joules per gram-degree Celsius). A calorie is the specific heat capacity of 1 gram of water.

**SYSTEM:** In chemistry and other sciences, the term "system" usually refers to any set of interactions isolated from the rest of the universe. Anything outside of the system, including all factors and forces irrelevant to a discussion of that system, is known as the environment.

**THERMAL ENERGY:** Heat energy resulting from internal kinetic energy.

**THERMAL EQUILIBRIUM:** A situation in which two systems have the same temperature. As a result, there is no exchange of heat between them.

**THERMODYNAMICS:** The study of the relationships between heat, work, and energy.

**THERMOMETER:** A device that gauges temperature by measuring a temperature-dependent property, such as the expansion of a liquid in a sealed tube, or resistance to electric current.

**THERMOMETRIC MEDIUM:** A substance whose physical properties change with temperature. A mercury or alcohol thermometer measures such changes.

**THIRD LAW OF THERMODYNAMICS:** A law of thermodynamics stating that at the temperature of absolute zero, entropy also approaches zero. Zero entropy contradicts the second law of thermodynamics, meaning that absolute zero is therefore impossible to reach.

liding, and the collisions that occur are more energetic. The likelihood is therefore increased that any particular collision will result in the energy necessary to break chemical bonds, and thus bring about the rearrangements in molecules needed for a reaction.

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# MASS, DENSITY, AND VOLUME

## CONCEPT

Among the physical properties studied by chemists and other scientists, mass is one of the most fundamental. All matter, by definition, has mass. Mass, in turn, plays a role in two properties important to the study of chemistry: density and volume. All of these—mass, density, and volume—are simple concepts, yet in order to work in chemistry or any of the other hard sciences, it is essential to understand these types of measurement. Measuring density, for instance, aids in determining the composition of a given substance, while volume is a necessary component to using the gas laws.

## HOW IT WORKS

### Fundamental Properties in Relation to Volume and Density

Most qualities of the world studied by scientists can be measured in terms of one or more of four properties: length, mass, time, and electric charge. The volume of a cube, for instance, is a unit of length cubed—that is, length multiplied by "width," which is then multiplied by "height."

Width and height are not, for the purposes of science, distinct from length: they are simply versions of it, distinguished by their orientation in space. Length provides one dimension, while width provides a second perpendicular to the third. Height, perpendicular both to length and width, makes the third spatial dimension—yet all of these are merely expressions of length differentiated according to direction.

**VOLUME AND DENSITY DEFINED.** Volume, then, is measured in terms of length, and can be defined as the amount of three-dimensional space an object occupies. Volume is usually expressed in cubic units of length—for example, the milliliter (mL), also known as the cubic centimeter (cc), is equal to $6.10237 \cdot 10^{-2}$ $in^3$. As its name implies, there are 1,000 milliliters in a liter.

Density is the ratio of mass to volume—or, to put its definition in terms of fundamental properties, of mass divided by cubed length. Density can also be viewed as the amount of matter within a given area. In the SI system, density is typically expressed as grams per cubic centimeter ($g/cm^3$), equivalent to 62.42197 pounds per cubic foot in the English system.

### Mass

**MASS DEFINED.** Though length is easy enough to comprehend, mass is more involved. In his second law of motion, Sir Isaac Newton (1642-1727) defined mass as the ratio of force to gravity. This, of course, is a statement that belongs to the realm of physics; for a chemist, it is more useful—and also accurate—to define mass as the quantity of matter that an object contains.

Matter, in turn, can be defined as physical substance that occupies space; is composed of atoms (or in the case of subatomic particles, is part of an atom); is convertible into energy—and has mass. The form or state of matter itself is not important: on Earth it is primarily observed as a solid, liquid, or gas, but it can also be found (particularly in other parts of the universe) in a fourth state, plasma.



Astronauts Neil Armstrong and Buzz Aldrin, the first men to walk on the Moon, weighed less on the Moon than on Earth. The reason is because weight differs as a response to the gravitational pull of the planet, moon, or other body on which it is measured. Thus, a person weighs less on the Moon, because the Moon possesses less mass than Earth and exerts less gravitational force. *(NASA/Roger Ressmeyer/Corbis. Reproduced by permission.)*

The more matter an object contains, the more mass. To refer again to the laws of motion, in his first law, Newton identified inertia: the tendency of objects in motion to remain in motion, or of objects at rest to remain at rest, in a constant velocity unless they are acted upon by some outside force. Mass is a measure of inertia, meaning that the more mass something contains, the more difficult it is to put it into motion, or to stop it from moving.

**MASS VS. WEIGHT.** Most people who are not scientifically trained tend to think that mass and weight are the same thing, but this is like saying that apples and apple pies are the same. Of course, an apple is an ingredient in an apple pie, but the pie contains something else—actually, a number of other things, such as flour and sugar. In this analogy, mass is equivalent to the apple, and weight the pie, while the acceleration due to gravity is the "something else" in weight.

It is understandable why people confuse mass with weight, since most weight scales provide measurements in both pounds and kilograms. However, the pound (lb) is a unit of weight in the English system, whereas a kilogram



To determine whether a piece of gold is genuine or fake, one must measure the density of the substance. Here, a man evaluates gold pieces in Hong Kong. *(Christophe Loviny/Corbis. Reproduced by permission.)*

(kg) is a unit of mass in the metric and SI systems. Though the two are relatively convertible on Earth (1 lb = 0.4536 kg; 1 kg = 2.21 lb), they are actually quite different.

Weight is a measure of force, which Newton's second law of motion defined as the product of mass multiplied by acceleration. The acceleration component of weight is a result of Earth's gravitational pull, and is equal to 32 ft (9.8 m) per second squared. Thus a person's weight varies according to gravity, and would be different if measured on the Moon; mass, on the other hand, is the same throughout the universe. Given its invariable value, scientists typically speak in terms of mass rather than weight.

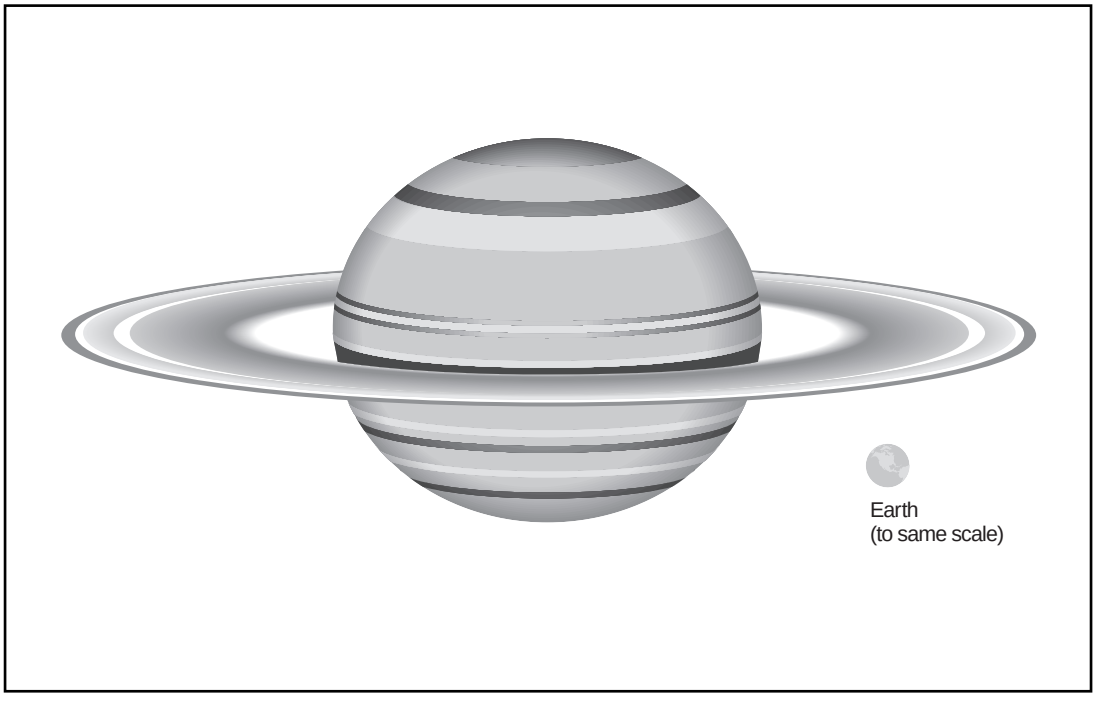
Weight differs as a response to the gravitational pull of the planet, moon, or other body on which it is measured. Hence a person weighs less on the Moon, because the Moon possesses less mass than Earth, and, thus, exerts less gravitational force. Therefore, it would be easier on the Moon to lift a person from the ground, but it would be no easier to move that person from a resting position, or to stop him or her from moving. This is because the person's mass, and hence his or her resistance to inertia, has not changed.

## REAL-LIFE APPLICATIONS

### Atomic Mass Units

Chemists do not always deal in large units of mass, such as the mass of a human body—which, of course, is measured in kilograms. Instead, the chemist's work is often concerned with measurements of mass for the smallest types of matter: molecules, atoms, and other elementary particles. To measure these even in terms of grams (0.001 kg) is absurd: a single atom of carbon, for instance, has a mass of $1.99 \cdot 10^{-23}$ g. In other words, a gram is about 50,000,000,000,000,000,000,000 times larger than a carbon atom—hardly a usable comparison.

Instead, chemists use an atom mass unit (abbreviated amu), which is equal to $1.66 \cdot 10^{-24}$ g. Even so, is hard to imagine determining the mass of single atoms on a regular basis, so chemists make use of figures for the average atomic mass of a particular element. The average atomic mass of carbon, for instance, is 12.01 amu. As is the case with any average, this means that some atoms—different isotopes of carbon—may weigh more or less, but the figure of 12.01




Although Saturn is much larger than Earth, it is much less dense.

amu is still reliable. Some other average atomic mass figures for different elements are as follows:

- Hydrogen (H): 1.008 amu
- Helium (He): 4.003 amu
- Lithium (Li): 6.941 amu
- Nitrogen (N): 14.01 amu
- Oxygen (O): 16.00
- Aluminum (Al): 26.98
- Chlorine (Cl): 35.46 amu
- Gold (Au): 197.0 amu
- Hassium (Hs): [265 amu]

The figure for hassium, with an atomic number of 108, is given in brackets because this number is the mass for the longest-lived isotope. The average value of mass for the molecules in a given compound can also be rendered in terms of atomic mass units: water ($H^2O$) molecules, for instance, have an average mass of 18.0153 amu. Molecules of magnesium oxide (MgO), which can be extracted from sea water and used in making ceramics, have an average mass much higher than for water: 40.304 amu.

These values are obtained simply by adding those of the atoms included in the molecule: since water has two hydrogen atoms and one oxygen, the average molecular mass is obtained by multiplying the average atomic mass of hydrogen by two, and adding it to the average atomic mass of oxygen. In the case of magnesium oxide, the oxygen is bonded to just one other atom—but magnesium, with an average atomic mass of 24.304, weighs much more than hydrogen.

## Molar Mass

It is often important for a chemist to know exactly how many atoms are in a given sample, particularly in the case of a chemical reaction between two or more samples. Obviously, it is impossible to count atoms or other elementary particles, but there is a way to determine whether two items—regardless of the elements or compounds involved—have the same number of elementary particles. This method makes use of the figures for average atomic mass that have been established for each element.

If the average atomic mass of the substance is 5 amu, then there should be a very large number of atoms (if it is an element) or molecules (if it is a compound) of that substance having a total mass of 5 grams (g). Similarly, if the average atomic mass of the substance is 7.5 amu, then there should be a very large number of atoms or molecules of that substance having a total mass of 7.5 g. What is needed, clearly, is a very large number by which elementary particles must be

multiplied in order to yield a mass whose value in grams is equal to the value, in amu, of its average atomic mass. This is known as Avogadro's number.

**AVOGADRO'S NUMBER.** The first scientist to recognize a meaningful distinction between atoms and molecules was Italian physicist Amedeo Avogadro (1776-1856). Avogadro maintained that gases consisted of particles—which he called molecules—that in turn consisted of one or more smaller particles. He further reasoned that one liter of any gas must contain the same number of particles as a liter of another gas.

In order to discuss the behavior of molecules, it was necessary to set a large quantity as a basic unit, since molecules themselves are very small. This led to the establishment of what is known as Avogadro's number, equal to $6.022137 \times 10^{23}$ (more than 600 billion trillion.)

The magnitude of Avogadro's number is almost inconceivable. The same number of grains of sand would cover the entire surface of Earth at a depth of several feet. The same number of seconds, for instance, is about 800,000 times as long as the age of the universe (20 billion years). Avogadro's number—named after the man who introduced the concept of the molecule, but only calculated years after his death—serves a very useful purpose in computations involving molecules.

**THE MOLE.** To compare two substances containing the same number of atoms or molecules, scientists use the mole, the SI fundamental unit for "amount of substance." A mole (abbreviated mol) is, generally speaking, Avogadro's number of atoms or molecules; however, in the more precise SI definition, a mole is equal to the number of carbon atoms in 12.01 g (0.03 lb) of carbon. Note that, as stated earlier, carbon has an average atomic mass of 12.01 amu. This is no coincidence, of course: multiplication of the average atomic mass by Avogadro's number yields a figure in grams equal to the value of the average atomic mass in amu.

The term "mole" can be used in the same way we use the word "dozen." Just as "a dozen" can refer to twelve cakes or twelve chickens, so "mole" always describes the same number of molecules. Just as one liter of water, or one liter of mercury, has a certain mass, a mole of any given substance has its own particular mass, expressed in grams. A mole of helium, for instance, has a mass of 4.003 g (0.01 lb), whereas a mole of iron is 55.85 g (0.12 lb) These figures represent the molar mass for each: that is, the mass of 1 mol of a given substance.

Once again, the value of molar mass in grams is the same as that of the average atomic mass in amu. Also, it should be clear that, given the fact that helium weighs much less than air—the reason why helium-filled balloons float—a quantity of helium with a mass of 4.003 g must be a great deal of helium. And indeed, as indicated earlier, the quantity of atoms or molecules in a mole is sufficiently great to make a sample that is large, but still usable for the purposes of study or comparison.

## Measuring Volume

Mass, because of its fundamental nature, is sometimes hard to comprehend, and density requires an explanation in terms of mass and volume. Volume, on the other hand, appears to be quite straightforward—and it is, when one is describing a solid of regular shape. In other situations, however, volume measurement is more complicated.

As noted earlier, the volume of a cube can be obtained simply by multiplying length by width by height. There are other means for measuring the volume of other straight-sided objects, such as a pyramid. Still other formulae, which make use of the constant $\pi$ (roughly equal to 3.14) are necessary for measuring the volume of a cylinder, a sphere, or a cone.

For an object that is irregular in shape, however, one may have to employ calculus—but the most basic method is simply to immerse the object in water. This procedure involves measuring the volume of the water before and after immersion, and calculating the difference. Of course, the object being measured cannot be water-soluble; if it is, its volume must be measured in a non-water-based liquid such as alcohol.

**LIQUID AND GAS VOLUME.** Measuring liquid volumes is even easier than for solids, given the fact that liquids have no definite shape, and will simply take the shape of the container in which they are placed. Gases are similar to liquids in the sense that they expand to fit their container; however, measurement of gas volume is a more involved process than that used to measure either liquids or solids, because gases are

highly responsive to changes in temperature and pressure.

If the temperature of water is raised from its freezing point to its boiling point—from 32°F (0°C) to 212°F (100°C)—its volume will increase by only 2%. If its pressure is doubled from 1 atm (defined as normal air pressure at sea level) to 2 atm, volume will decrease by only 0.01%. Yet if air were heated from 32° to 212°F, its volume would increase by 37%; if its pressure were doubled from 1 atm to 2, its volume would decrease by 50%.

Not only do gases respond dramatically to changes in temperature and pressure, but also, gas molecules tend to be non-attractive toward one another—that is, they tend not to stick together. Hence, the concept of "volume" in relation to a gas is essentially meaningless unless its temperature and pressure are known.

## Comparing Densities

In the discussion of molar mass above, helium and iron were compared, and we saw that the mass of a mole of iron was about 14 times as great as that of a mole of helium. This may seem like a fairly small factor of difference between them: after all, helium floats on air, whereas iron (unless it is arranged in just the right way, for instance, in a tanker) sinks to the bottom of the ocean. But be careful: the comparison of molar mass is only an expression of the mass of a helium atom as compared to the mass of an iron atom. It makes no reference to density, which is the ratio of mass to volume.

Expressed in terms of the ratio of mass to volume, the difference between helium and iron becomes much more pronounced. Suppose, on the one hand, one had a gallon jug filled with iron. How many gallons of helium does it take to equal the mass of the iron? Fourteen? Try again: it takes more than 43,000 gallons of helium to equal the mass of the iron in one gallon jug! Clearly, what this shows is that the density of iron is much, much greater than that of helium.

This, of course, is hardly a surprising revelation; still, it is sometimes easy to get confused by comparisons of mass as opposed to comparisons of density. One might even get tricked by the old elementary-school brain-teaser that goes something like this: "Which is heavier, a ton of feathers or a ton of cannonballs?" Of course neither is heavier, but the trick element in the question relates to the fact that it takes a much greater volume of feathers (measured in cubic feet, for instance) than of cannonballs to equal a ton.

One of the interesting things about density, as distinguished from mass and volume, is that it has nothing to do with the amount of material. A kilogram of iron differs from 10 kg of iron both in mass and volume, but the density of both samples is the same. Indeed, as discussed below, the known densities of various materials make it possible to determine whether a sample of that material is genuine.

**COMPARING DENSITIES.** As noted several times, the densities of numerous materials are known quantities, and can be easily compared. Some examples of density, all expressed in terms of grams per cubic centimeter, are listed below. These figures are measured at a temperature of 68°F (20°C), and for hydrogen and oxygen, the value was obtained at normal atmospheric pressure (1 atm):

Comparisons of Densities for Various Substances:

- Oxygen: 0.00133 g/cm$^3$
- Hydrogen: 0.000084 g/cm$^3$
- Ethyl alcohol: 0.79 g/cm$^3$
- Ice: 0.920 g/cm$^3$
- Water: 1.00 g/cm$^3$
- Concrete: 2.3 g/cm$^3$
- Iron: 7.87 g/cm$^3$
- Lead: 11.34 g/cm$^3$
- Gold: 19.32 g/cm$^3$

## Specific Gravity

**IS IT REALLY GOLD?** Note that pure water (as opposed to sea water, which is 3% more dense) has a density of 1.0 g per cubic centimeter. Water is thus a useful standard for measuring the specific gravity of other substances, or the ratio between the density of that substance and the density of water. Since the specific gravity of water is 1.00—also the density of water in g/cm$^3$—the specific gravity of any substance (a number, rather than a number combined with a unit of measure) is the same as the value of its own density in g/cm$^3$.

Comparison of densities make it possible to determine whether a piece of jewelry alleged to be solid gold is really genuine. To determine the answer, one must drop the sample in a beaker of water with graduated units of measure clearly

## KEY TERMS

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

**AVERAGE ATOMIC MASS:** A figure used by chemists to specify the mass—in atomic mass units—of the average atom in a large sample. The average atomic mass of carbon, for instance, is 12.01 amu. If a substance is a compound, the average atomic mass of all atoms in a molecule of that substance must be added together to yield the average molecular mass of that substance.

**AVOGADRO'S NUMBER:** A figure, named after Italian physicist Amedeo Avogadro (1776-1856), equal to $6.022137 \times +0^{23}$. Avogadro's number indicates the number of atoms, molecules, or other elementary particles in a mole.

**DENSITY:** The ratio of mass to volume—in other words, the amount of matter within a given area. In the SI system, density is typically expressed as grams per cubic centimeter ($g/cm^3$), equal to 62.42197 pounds per cubic foot in the English system.

**MASS:** The amount of matter an object contains.

**MATTER:** Physical substance that occupies space, has mass, is composed of atoms (or in the case of subatomic particles, is part of an atom), and is convertible to energy.

**MILLILITER:** One of the most commonly used units of volume in the SI system of measures. The milliliter (abbreviated mL), also known as a cubic centimeter (cc), is equal to $6.10237 \cdot 10^{-2}$ cubic inches in the English system. As the name implies, there are 1,000 milliliters in a liter.

**MOLAR MASS:** The mass, in grams, of 1 mole of a given substance. The value in grams of molar mass is always equal to the value, in atomic mass units, of the average atomic mass of that substance: thus, carbon has a molar mass of 12.01 g, and an average atomic mass of 12.01 amu.

**MOLE:** The SI fundamental unit for "amount of substance." A mole is, generally speaking, Avogadro's number of atoms, molecules, or other elementary particles; however, in the more precise SI definition, a mole is equal to the number of carbon atoms in 12.01 g of carbon.

**SPECIFIC GRAVITY:** The density of an object or substance relative to the density of water; or more generally, the ratio between the densities of two objects or substances. Since the specific gravity of water is 1.00—also the density of water in $g/cm^3$—the specific gravity of any substance is the same as the value of its own density in $g/cm^3$. Specific gravity is simply a number, without any unit of measure.

**VOLUME:** The amount of three-dimensional space an object occupies. Volume is usually expressed in cubic units of length—for instance, the milliliter.

**WEIGHT:** The product of mass multiplied by the acceleration due to gravity (32 ft or 9.8 $m/sec^2$). A pound is a unit of weight, whereas a kilogram is a unit of mass.

marked. Suppose the item has a mass of 10 g. The density of gold is 19 g/cm$^3$, and because density is equal to mass divided by volume, the volume of water displaced should be equal to the mass divided by the density. The latter figure is equal to 10 g divided by 19 g/cm$^3$, or 0.53 ml. Suppose that instead, the item displaced 0.88 ml of water. Clearly it is not gold, but what is it?

Given the figures for mass and volume, its density is equal to 11.34 g/cm$^3$—which happens to be the density of lead. If, on the other hand, the amount of water displaced were somewhere between the values for pure gold and pure lead, one could calculate what portion of the item was gold and which lead. It is possible, of course, that it could contain some other metal, but given the high specific gravity of lead, and the fact that its density is relatively close to that of gold, lead is a favorite gold substitute among jewelry counterfeiters.

**SPECIFIC GRAVITY AND THE DENSITIES OF PLANETS.** Most rocks near the surface of Earth have a specific gravity somewhere between 2 and 3, while the specific gravity of the planet itself is about 5. How do scientists know that the density of Earth is around 5 g/cm$^3$? The computation is fairly simple, given the fact that the mass and volume of the planet are known. And given the fact that most of what lies close to Earth's surface—sea water, soil, rocks—has a specific gravity well below 5, it is clear that Earth's interior must contain high-density materials, such as nickel or iron. In the same way, calculations regarding the density of other objects in the Solar System provide a clue as to their interior composition.

This brings the discussion back around to a topic raised much earlier in this essay, when comparing the weight of a person on Earth versus that person's weight on the Moon. It so happens that the Moon is smaller than Earth, but that is not the reason it exerts less gravitational pull: as noted earlier, the gravitational force a planet, moon, or other body exerts is related to its mass, not its size.

It so happens, too, that Jupiter is much larger than Earth, and that it exerts a gravitational pull much greater than that of Earth. This is because it has a mass many times as great as Earth's. But what about Saturn, the second-largest planet in the Solar System? In size it is only about 17% smaller than Jupiter, and both are much, much larger than Earth. Yet a person would weigh much less on Saturn than on Jupiter, because Saturn has a mass much smaller than Jupiter's. Given the close relation in size between the two planets, it is clear that Saturn has a much lower density than Jupiter, or in fact even Earth: the great ringed planet has a specific gravity of less than 1.

## WHERE TO LEARN MORE


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# MATTER

## PROPERTIES OF MATTER

## GASES

# PROPERTIES OF MATTER

## CONCEPT

Matter is physical substance that occupies space, has mass, is composed of atoms—or, in the case of subatomic particles, is part of an atom—and is convertible to energy. On Earth, matter appears in three clearly defined forms—solid, liquid, and gas—whose varying structural characteristics are a function of the speeds at which its molecules move in relation to one another. A single substance may exist in any of the three phases: liquid water, for instance, can be heated to become steam, a vapor; or, when sufficient heat is removed from it, it becomes ice, a solid. These are merely physical changes, which do not affect the basic composition of the substance itself: it is still water. Matter, however, can and does undergo chemical changes, which (as with the various states or phases of matter) are an outcome of activity at the atomic and molecular level.

## HOW IT WORKS

### Matter and Energy

One of the characteristics of matter noted in its definition above is that it is convertible to energy. We rarely witness this conversion, though as Albert Einstein (1879-1955) showed with his Theory of Relativity, it occurs in a massive way at speeds approaching that of light.

Einstein's famous formula, $E = mc^2$, means that every item possesses a quantity of energy equal to its mass multiplied by the squared speed of light. Given the fact that light travels at 186,000 mi (299,339 km) per second, the quantities of energy available from even a tiny object traveling at that speed are enormous indeed. This is the basis for both nuclear power and nuclear weaponry, each of which uses some of the smallest particles in the known universe to produce results that are both amazing and terrifying.

Even in everyday life, it is still possible to observe the conversion of mass to energy, if only on a very small scale. When a fire burns—that is, when wood experiences combustion in the presence of oxygen, and undergoes chemical changes—a tiny fraction of its mass is converted to energy. Likewise, when a stick of dynamite explodes, it too experiences chemical changes and the release of energy. The actual amount of energy released is, again, very small: for a stick of dynamite weighing 2.2 lb (1 kg), the portion of its mass that "disappears" is be equal to 6 parts out of 100 billion.

Actually, none of the matter in the fire or the dynamite blast disappears: it simply changes forms. Most of it becomes other types of matter—perhaps new compounds, and certainly new mixtures of compounds. A very small part, as we have seen, becomes energy. One of the most fundamental principles of the universe is the conservation of energy, which holds that within a system isolated from all other outside factors, the total amount of energy remains the same, though transformations of energy from one form to another take place. In this situation, some of the energy remains latent, or "in reserve" as matter, while other components of the energy are released; yet the total amount of energy remains the same.

## Physical and Chemical Changes

In discussing matter—as, for instance, in the context of matter transforming into energy—one may speak in physical or chemical terms, or both. Generally speaking, physicists study physical properties and changes, while chemists are concerned with chemical processes and changes.

A physicist views matter in terms of its mass, temperature, mechanical properties (for example, elasticity); electrical conductivity; and other structural characteristics. The chemical makeup of matter, on the other hand, is of little concern to a physicist. For instance, in analyzing a fire or an explosion, the physicist is not concerned with the interactions of combustible or explosive materials and oxygen. The physicist's interest, rather, is in questions such as the amount of heat in the fire, the properties of the sound waves emitted in the explosion of the dynamite, and so on.

The changes between different states or phases of matter, as they are discussed below, are physical changes. If water boils and vaporizes as steam, it is still water; likewise if it freezes to become solid ice, nothing has changed with regard to the basic chemical structure of the $H_2O$ molecules that make up water. But if water reacts with another substance to form a new compound, it has undergone chemical change. Likewise, if water molecules experience electrolysis, a process in which electric current is used to decompose $H_2O$ into molecules of $H_2$ and $O_2$, this is also a chemical change.

Similarly, a change from matter to energy, while it is also a physical change, typically involves some chemical or nuclear process to serve as "midwife" to that change. Yet physical and chemical changes have at least one thing in common: they can be explained in terms of behavior at the atomic or molecular level. This is true of many physical processes—and of all chemical ones.

## Atoms

In his highly readable *Six Easy Pieces*—a work that includes considerable discussion of chemistry as well as physics—the great American physicist Richard Feynman (1918-1988) asked, "If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generations of creatures, what statement would contain the most information in the fewest words?"

The answer he gave was this: "I believe it is the atomic hypothesis (or the atomic fact, or whatever you wish to call it) that all things are made of atoms—little articles that move around in perpetual motion, attracting each other when they are a little distance apart, but repelling upon being squeezed into one another. In that sentence, you will see, there is an enormous amount of information about the world, if just a little imagination and thinking are applied."

Indeed, what Feynman called the "atomic hypothesis" is one of the most important keys to understanding both physical and chemical changes. The behavior of particles at the atomic level has a defining role in the shape of the world studied by the sciences, and an awareness of this behavior makes it easier to understand physical processes, such as changes of state between solid, liquid, and gas; chemical processes, such as the formation of new compounds; and other processes, such as the conversion of matter to energy, which involve both physical and chemical changes. Only when one comprehends the atomic structure of matter is it possible to move on to the chemical elements that are the most basic materials of chemistry.

**Structure of the atom.** As Feynman went on to note, atoms are so tiny that if an apple were magnified to the size of Earth, the atoms in it would each be about the size of a regular apple. Clearly, atoms and other atomic particles are far too small to be glimpsed even by the most highly powered optical microscope. Yet physicists and other scientists are able to study the behavior of atoms, and by doing so, they are able to form a picture of what occurs at the atomic level.

An atom is the fundamental particle in a chemical element. The atom is not, however, the smallest particle in the universe: atoms are composed of subatomic particles, including protons, neutrons, and electrons. These are distinguished from one another in terms of electric charge: as with the north and south poles of magnets, positive and negative charges attract one another, but like charges repel. (In fact, magnetism is simply a manifestation of a larger electromagnetic force that encompasses both electricity and magnetism.)

Clustered at the center, or nucleus, of the atom are protons, which are positively charged, and neutrons, which exert no charge. Spinning around the nucleus are electrons, which exert a negative charge. The vast majority of the atom's mass is made up by the protons and neutrons, which have approximately the same mass; that of the electron is much smaller. If an electron had a mass of 1—not a unit, but simply a figure used for comparison—the mass of the proton would be 1,836, and of the neutron 1,839.

Atoms of the same element always have the same number of protons, and since this figure is unique for a given element, each element is assigned an atomic number equal to the number of protons in its nucleus. Two atoms may have the same number of protons, and thus be of the same element, yet differ in their number of neutrons. Such atoms are called isotopes.

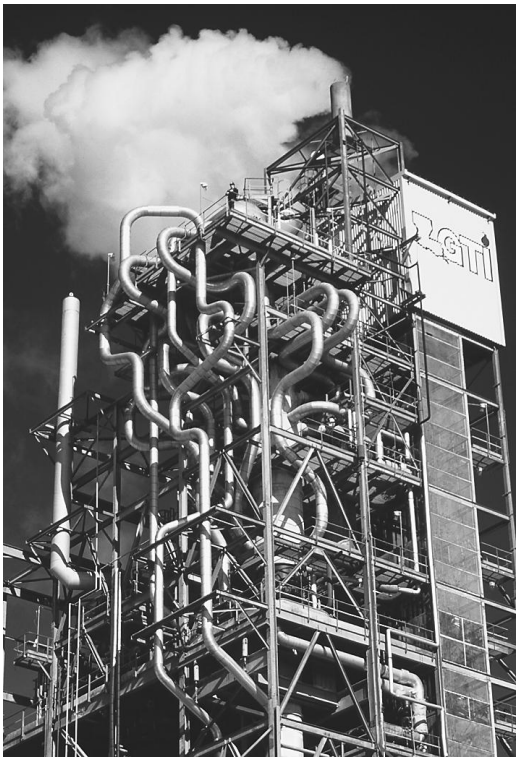
The number of electrons is usually the same as the number of protons, and thus atoms have a neutral charge. In certain situations, however, the atom may lose or gain one or more electrons and acquire a net charge, becoming an ion. But electric charge, like energy, is conserved, and the electrons are not "lost" when an atom becomes an ion: they simply go elsewhere.

It is useful, though far from precise, to compare the interior of an atom to a planet spinning very quickly around a sun. If the nucleus were our own Sun, then the electrons spinning at the edge of the atom would be on an orbit somewhere beyond Mars: in other words, the ratio between the size of the nucleus and the furthest edge of the atom is like that between the Sun's diameter and an orbital path about 80 million miles beyond Mars.

One of many differences between an atom and a solar system, however, is the fact that the electrons are spinning around the nucleus at a relative rate of motion much, much greater than any planet is revolving around the Sun. Furthermore, what holds the atom together is not gravitational force, as in the Solar System, but electromagnetic force. A final and critical difference is the fact that electrons move in much more complex orbital patterns than the elliptical paths that planets make in their movement around the Sun.

## MOLECULES

Though an atom is the fundamental unit of matter, most of the substances people encounter in the world are not pure elements such as oxygen or iron. They are compounds in which atoms of more than one element join—usually in molecules. All molecules are composed of more than one atom, but not necessarily of more than one element: oxygen, for instance, generally appears in the form of molecules in which two oxygen atoms are bonded. Because of this, pure oxygen is represented by the chemical symbol $O_2$, as opposed to the symbol for the element oxygen, which is simply O.



A COAL GASIFICATION PLANT. COAL GASIFICATION MAKES IT POSSIBLE TO BURN "CLEAN" COAL. *(Roger Ressmeyer/Corbis. Reproduced by permission.)*

One of the most well-known molecular forms in the world is water, or $H_2O$, composed of two hydrogen atoms and one oxygen atom. The arrangement is extremely precise and never varies: scientists know, for instance, that the two hydrogen atoms join the oxygen atom (which is much larger than the hydrogen atoms) at an angle of 105°3'. Since the oxygen atom is much larger than the two hydrogens, its shape can be compared to a basketball with two softballs attached.

Other molecules are much more complex than those of water, and some are much, much more complex, a fact reflected in the sometimes

lengthy names and complicated symbolic representations required to identify their chemical components. On the other hand, not all materials are made up of molecules: salt, for instance, is an ionic solid, as discussed below.

## Quantifying Atoms and Molecules

The nucleus of an atom is about $10^{-13}$ cm in diameter, and the diameter of the entire atom is about $10^{-8}$ cm—about 0.0000003937 in. Obviously, special units are required for describing the size of atoms, and usually measurements are provided in terms of the angstrom, equal to $10^{-10}$ m, or $10^{-8}$ cm. To put this on some sort of imaginable scale, there are 10 million angstroms in a millimeter.

Measuring the spatial dimensions of an atom, however, is not as important as measuring its mass—and naturally, the mass of an atom is also almost inconceivably small. For instance, it takes about $5.0 \cdot 10^{23}$ carbon atoms to equal just one gram of mass. Again, the numbers boggle the mind, but the following may put this into perspective. We have already established just how tiny an angstrom is; now consider the following. If $5.0 \cdot 10^{23}$ angstrom lengths were laid end to end, they would stretch for a total of about 107,765 round trips from Earth to the Sun!

It is obvious, then, that an entirely different unit should be used for measuring the mass of an atom, and for this purpose, chemists and other scientists use an atom mass unit (abbreviated amu). The latter is equal to $1.66 \cdot 10^{-24}$ g. Even so, scientists can hardly be expected to be constantly measuring the mass of individual atoms; rather, they rely on figures determined for the average atomic mass of a particular element.

Average atomic mass figures range from 1.008 amu for hydrogen to over 250 amu for elements of very high atomic numbers. Figures for average atomic mass can be used to determine the average mass of a molecule as well, simply by combining the average atomic mass figures for each atom the molecule contains. A water molecule, for instance, has an average mass equal to the average atomic mass of hydrogen multiplied by two, and added to the average atomic mass of oxygen.

**Avogadro's number and the mole.** Just as using average atomic mass is much more efficient than measuring the mass of individual atoms or molecules, scientists need a useful means for comparing atoms or molecules of different substances—and for doing so in such a way that they know they are analyzing equal numbers of particles. This cannot be done in terms of mass, because the number of atoms in each sample would vary: a gram of hydrogen, for instance, would contain about 12 times as many atoms as a gram of carbon, which has an average atomic mass of 12.01 amu. What is needed, instead, is a way to designate a certain number of atoms or molecules, such that accurate comparisons are possible.

In order to do this, scientists make use of a figure known as Avogadro's number. Named after Italian physicist Amedeo Avogadro (1776-1856), it is equal to $6.022137 \times 10^{23}$ Earlier, we established the almost inconceivable scale represented by the figure $5.0 \cdot 10^{23}$; here we are confronted with a number 20% larger. But Avogadro's number, which is equal to 6,022,137 followed by 17 zeroes, is more than simply a mind-boggling series of digits.

In general terms, Avogadro's number designates the quantity of molecules (and sometimes atoms, if the substance in question is an element that, unlike oxygen, appears as single atoms) in a mole (abbreviated mol). A mole is the SI unit for "amount of substance," and is defined precisely as the number of carbon atoms in 12.01 g of carbon. It is here that the value of Avogadro's number becomes clear: as noted, carbon has an average atomic mass of 12.01 amu, and multiplication of the average atomic mass by Avogadro's number yields a figure in grams equal to the value of the average atomic mass in atomic mass units.

**Molar mass and density.** By comparison, a mole of helium has a molar mass of 4.003 g (0.01 lb) The molar mass of iron (that is, the mass of 1 mole of iron) is 55.85 g (0.12 lb) Note that there is not a huge ratio of difference between the molar mass of iron and that of helium: iron has a molar mass about 14 times greater. This, of course, seems very small in light of the observable differences between iron and helium: after all, who ever heard of a balloon filled with iron, or a skyscraper with helium girders?

The very striking differences between iron and helium, clearly, must come from something other than the molar mass differential between

them. Of course, a mole of iron contains the same number of atoms as a mole of helium, but this says nothing about the relative density of the two substances. In terms of volume—that is, the amount of space that something occupies—the difference is much more striking: the volume of a mole of helium is about 43,000 times as large as that of a mole of iron.

What this tells us is that the densities of iron and helium—the amount of mass per unit of volume—are very different. This difference in density is discussed in the essay on Mass, Density, and Volume; here the focus is on a larger judgment that can be formed by comparing the two densities. Helium, of course, is almost always in the form of a gas: to change it to a solid requires a temperature near absolute zero. And iron is a solid, meaning that it only turns into a liquid at extraordinarily high temperatures. These differences in overall structure can, in turn, be attributed to the relative motion, attraction, and energy of the molecules in each.

### Molecular Attraction and Motion

At the molecular level, every item of matter in the world is in motion, and the rate of that motion is a function of the attraction between molecules. Furthermore, the rate at which molecules move in relation to one another determines phase of matter—that is, whether a particular item can be described as solid, liquid, or gas. The movement of molecules generates kinetic energy, or the energy of movement, which is manifested as thermal energy—what people call "heat" in ordinary language. (The difference between thermal energy and heat is explained in the essay on Temperature and Heat.) In fact, thermal energy is the result of molecules' motion relative to one another: the faster they move, the greater the kinetic energy, and the greater the "heat."

When the molecules in a material move slowly—merely vibrating in place—they exert a strong attraction toward one another, and the material is called a solid. Molecules of liquid, by contrast, move at moderate speeds and exert a moderate attraction. A material substance whose molecules move at high speeds, and therefore exert little or no attraction, is known as a gas. In short, the weaker the attraction, the greater the rate of relative motion—and the greater the amount of thermal energy the object contains.

## REAL-LIFE APPLICATIONS

### Types of Solids

Particles of solids resist attempts to compress them, or push them together, and because of their close proximity, solid particles are fixed in an orderly and definite pattern. As a result, a solid usually has a definite volume and shape.

A crystalline solid is a type of solid in which the constituent parts are arranged in a simple, definite geometric pattern that is repeated in all directions. But not all crystalline solids are the same. Table salt is an example of an ionic solid: a form of crystalline solid that contains ions. When mixed with a solvent such as water, ions from the salt move freely throughout the solution, making it possible to conduct an electric current.

Regular table sugar (sucrose) is a molecular solid, or one in which the molecules have a neutral electric charge—that is, there are no ions present. Therefore, a solution of water and sugar would not conduct electricity. Finally, there are crystalline solids known as atomic solids, in which atoms of one element bond to one another. Examples include diamonds (made of pure carbon), silicon, and all metals.

Other solids are said to be amorphous, meaning that they possess no definite shape. Amorphous solids—an example of which is clay—either possess very tiny crystals, or consist of several varieties of crystal mixed randomly. Still other solids, among them glass, do not contain crystals.

### Freezing and Melting

**VIBRATIONS AND FREEZING.** Because of their slow movement in relation to one another, solid particles exert strong attractions; yet as slowly as they move, solid particles do move—as is the case with all forms of matter at the atomic level. Whereas the particles in a liquid or gas move fast enough to be in relative motion with regard to one another, however, solid particles merely vibrate from a fixed position.

As noted earlier, the motion and attraction of particles in matter has a direct effect on thermal energy, and thus on heat and temperature. The cooler the solid, the slower and weaker the vibrations, and the closer the particles are to one

another. Thus, most types of matter contract when freezing, and their density increases. Absolute zero, or 0K on the Kelvin scale of temperature—equal to –459.67°F (–273°C)—is the point at which vibration virtually ceases.

Note that the vibration virtually stops, but does not totally stop. In fact, as established in the third law of thermodynamics, absolute zero is impossible to achieve: thus, the relative motion of molecules never ceases. The lowest temperature actually achieved, at a Finnish nuclear laboratory in 1993, is $2.8 \cdot 10^{-10}$ K, or 0.00000000028K—still above absolute zero.

**UNUSUAL CHARACTERISTICS OF SOLID AND LIQUID WATER.** The behavior of water when frozen is interesting and exceptional. Above 39.2°F (4°C) water, like most substances, expands when heated. In other words, the molecules begin moving further apart as expected, because—in this temperature range, at least—water behaves like other substances, becoming "less solid" as the temperature increases.

Between 32°F (0°C) and 39.2°F (4°C), however, water actually contracts. In this temperature range, it is very "cold" (that is, it has relatively little heat), but it is not frozen. The density of water reaches its maximum—in other words, water molecules are as closely packed as they can be—at 39.2°F; below that point, the density starts to decrease again. This is highly unusual: in most substances, the density continues to increase with lowered temperatures, whereas water is actually most dense slightly above the freezing point.

Below the freezing point, then, water expands, and therefore when water in pipes freezes, it may increase in volume to the point where it bursts the pipe. This is also the reason why ice floats on water: its weight is less than that of the water it has displaced, and thus it is buoyant. Additionally, the buoyant qualities of ice atop very cold water helps explain the behavior of lake water in winter; although the top of a lake may freeze, the entire lake rarely freezes solid—even in the coldest of inhabited regions.

Instead of freezing from the bottom up, as it would if ice were less buoyant than the water, the lake freezes from the top down—an important thing to remember when ice-fishing! Furthermore, water in general (and ice in particular) is a poor conductor of heat, and thus little of the heat from the water below it escapes. Therefore, the lake does not freeze completely—only a layer at the top—and this helps preserve animal and plant life in the body of water.

**MELTING.** When heated, particles begin to vibrate more and more, and therefore move further apart. If a solid is heated enough, it loses its rigid structure and becomes a liquid. The temperature at which a solid turns into a liquid is called the melting point, and melting points are different for different substances. The melting point of a substance, incidentally, is the same as its freezing point: the difference is a matter of orientation—that is, whether the process is one of a solid melting to become a liquid, or of a liquid freezing to become a solid.

The energy required to melt 1 mole of a solid substance is called the molar heat of fusion. It can be calculated by the formula $Q = sm\delta T$, where Q is energy, s is specific heat capacity, m is mass, and $\delta T$ means change in temperature. (In the symbolic language often employed by scientists, the Greek letter $\delta$, or delta, stands for "change in.") Specific heat capacity is measured in units of J/g • °C (joules per gram-degree Celsius), and energy in joules or kilojoules (kJ)—that is, 1,000 joules.

In melting, all the thermal energy in a solid is used in breaking up the arrangement of crystals, called a lattice. This is why water melted from ice does not feel any warmer than the ice did: the thermal energy has been expended, and there is none left over for heating the water. Once all the ice is melted, however, the absorbed energy from the particles—now moving at much greater speeds than when the ice was in a solid state—causes the temperature to rise.

For the most part, solids composed of particles with a higher average atomic mass require more energy—and hence higher temperatures—to induce the vibrations necessary for melting. Helium, with an average atomic mass of 4.003 amu, melts or freezes at an incredibly low temperature: –457.6°F (–272°C), or close to absolute zero. Water, for which, as noted earlier, the average atomic mass is the sum of the masses for its two hydrogen atoms and one oxygen atom, has an average molecular mass of 18.016 amu. Ice melts (or water freezes) at much higher temperatures than helium: 32°F (0°C). Copper, with an average atomic mass of 63.55 amu, melts at much, much higher temperatures than water: 1,985°F (1,085°C).

## LIQUIDS

The particles of a liquid, as compared to those of a solid, have more energy, more motion, and—generally speaking—less attraction to one another. The attraction, however, is still fairly strong: thus, liquid particles are in close enough proximity that the liquid resists attempts at compression.

On the other hand, their arrangement is loose enough that the particles tend to move around one another rather than simply vibrate in place the way solid particles do. A liquid is therefore not definite in shape. Due to the fact that the particles in a liquid are farther apart than those of a solid, liquids tend to be less dense than solids. The liquid phase of a substance thus tends to be larger in volume than its equivalent in solid form. Again, however, water is exceptional in this regard: liquid water actually takes up less space than an equal mass of frozen water.

## BOILING

When a liquid experiences an increase in temperature, its particles take on energy and begin to move faster and faster. They collide with one another, and at some point the particles nearest the surface of the liquid acquire enough energy to break away from their neighbors. It is at this point that the liquid becomes a gas or vapor.

As heating continues, particles throughout the liquid begin to gain energy and move faster, but they do not immediately transform into gas. The reason is that the pressure of the liquid, combined with the pressure of the atmosphere above the liquid, tends to keep particles in place. Those particles below the surface, therefore, remain where they are until they acquire enough energy to rise to the surface.

The heated particle moves upward, leaving behind it a hollow space—a bubble. A bubble is not an empty space: it contains smaller trapped particles, but its small mass, relative to that of the liquid it disperses, makes it buoyant. Therefore, a bubble floats to the top, releasing its trapped particles as gas or vapor. At that point, the liquid is said to be boiling.

**THE EFFECT OF ATMOSPHERIC PRESSURE.** The particles thus have to overcome atmospheric pressure as they rise, which means that the boiling point for any liquid depends in part on the pressure of the surrounding air. Normal atmospheric pressure (1 atm) is equal to 14 lb/in$^2$ (1.013 x 10$^5$ Pa), and is measured at sea level. The greater the altitude, the less the air pressure, because molecules of air—since air is a gas, and therefore its particles are fast-moving and non-attractive—respond less to Earth's gravitational pull. This is why airplanes require pressurized cabins to maintain an adequate oxygen supply; but even at altitudes much lower than the flight path of an airplane, differences in air pressure are noticeable.

It is for this reason that cooking instructions often vary with altitude. Atop Mt. Everest, Earth's highest peak at about 29,000 ft (8,839 m) above sea level, the pressure is approximately one-third of normal atmospheric pressure. Water boils at a much lower temperature on Everest than it does elsewhere: 158°F (70°C), as opposed to 212°F (100°C) at sea level. Of course, no one lives on the top of Mt. Everest—but people do live in Denver, Colorado, where the altitude is 5,577 ft (1,700 m) and the boiling point of water is 203°F (95°C).

Given the lower boiling point, one might assume that food would cook faster in Denver than in New York, Los Angeles, or in any city close to sea level. In fact, the opposite is true: because heated particles escape the water so much faster at high altitudes, they do not have time to acquire the energy needed to raise the temperature of the water. It is for this reason that a recipe may include a statement such as "at altitudes above XX feet, add XX minutes to cooking time."

If lowered atmospheric pressure means a lowered boiling point, what happens in outer space, where there is no atmospheric pressure? Liquids boil at very, very low temperatures. This is one of the reasons why astronauts have to wear pressurized suits: if they did not, their blood would boil—even though space itself is incredibly cold.

**LIQUID TO GAS AND BACK AGAIN.** Note that the process of changing a liquid to a gas is similar to that which occurs when a solid changes to a liquid: particles gain heat and therefore energy, begin to move faster, break free from one another, and pass a certain threshold into a new phase of matter. And just as the freezing and melting point for a given substance are the same temperature—the only difference being one of orientation—the boiling

point of a liquid transforming into a gas is the same as the condensation point for a gas turning into a liquid.

The behavior of water in boiling and condensation makes possible distillation, one of the principal methods for purifying sea water in various parts of the world. First the water is boiled, then it is allowed to cool and condense, thus forming water again. In the process, the water separates from the salt, leaving it behind in the form of brine. A similar separation takes place when salt water freezes: because salt, like most crystalline solids, has a much lower freezing point than water, very little of it remains joined to the water in ice. Instead, the salt takes the form of a briny slush.

## Gases

A liquid that is vaporized, or any substance that exists normally as a gas, is quite different in physical terms from a solid or a liquid. This is illustrated by the much higher energy component in the molar heat of vaporization, or the amount of energy required to turn 1 mole of a liquid into a gas.

Consider, for instance, what happens to water when it experiences phase changes. Assuming that heat is added at a uniform rate, when ice reaches its melting point, there is only a relatively small period of time when the $H_2O$ is composed of both ice and liquid. But when the liquid reaches its boiling point, the water is present both as a liquid and a vapor for a much longer period of time. In fact, it takes almost seven times as much energy to turn liquid water into pure steam than it does to turn ice into purely liquid water. Thus, the molar heat of fusion for water is 6.02 kJ/mol, while the molar heat of vaporization is 40.6 kJ/mol.

Although liquid particles exert a moderate attraction toward one another, particles in a gas (particularly a substance that normally exists as a gas at ordinary temperatures on Earth) exert little to no attraction. They are thus free to move, and to move quickly. The overall shape and arrangement of gas is therefore random and indefinite—and, more importantly, the motion of gas particles provides much greater kinetic energy than is present in any other major form of matter on Earth.

The constant, fast, and random motion of gas particles means that they are regularly colliding and thereby transferring kinetic energy back and forth without any net loss of energy. These collisions also have the overall effect of producing uniform pressure in a gas. At the same time, the characteristics and behavior of gas particles indicate that they tend not to remain in an open container. Therefore, in order to have any pressure on a gas—other than normal atmospheric pressure—it is necessary to keep it in a closed container.

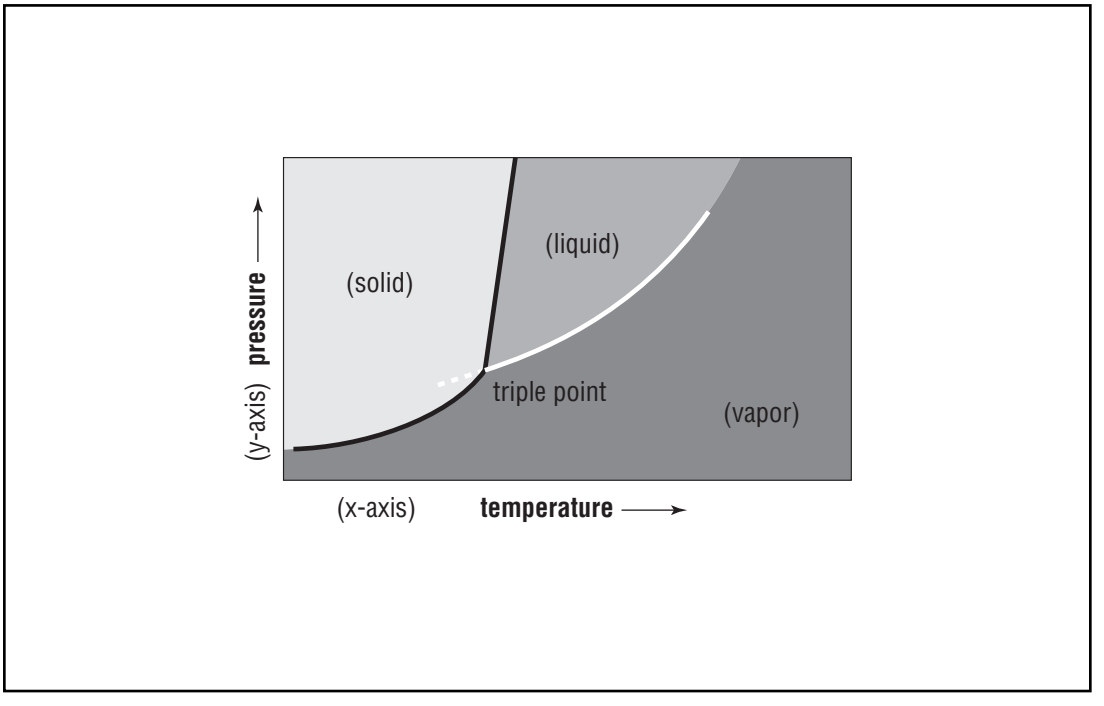
## The Phase Diagram

The vaporization of water is an example of a change of phase—the transition from one phase of matter to another. The properties of any substance, and the points at which it changes phase, are plotted on what is known as a phase diagram. The phase diagram typically shows temperature along the x-axis, and pressure along the y-axis.

For simple substances, such as water and carbon dioxide ($CO_2$), the solid form of the substance appears at a relatively low temperature and at pressures anywhere from zero upward. The line between solids and liquids, indicating the temperature at which a solid becomes a liquid at any pressure above a certain level, is called the fusion curve. Though it appears to be a more or less vertical line, it is indeed curved, indicating that at high pressures, a solid well below the normal freezing point may be melted to create a liquid.

Liquids occupy the area of the phase diagram corresponding to relatively high temperatures and high pressures. Gases or vapors, on the other hand, can exist at very low temperatures, but only if the pressure is also low. Above the melting point for the substance, gases exist at higher pressures and higher temperatures. Thus, the line between liquids and gases often looks almost like a 45° angle. But it is not a straight line, as its name, the vaporization curve, implies. The curve of vaporization demonstrates that at relatively high temperatures and high pressures, a substance is more likely to be a gas than a liquid.

**The critical point.** There are several other interesting phenomena mapped on a phase diagram. One is the critical point, found at a place of very high temperature and pressure along the vaporization curve. At the critical point, high temperatures prevent a liquid from remaining a liquid, no matter how high the pressure.




A PHASE DIAGRAM FOR WATER.

At the same time, the pressure causes gas beyond that point to become increasingly more dense, but due to the high temperatures, it does not condense into a liquid. Beyond the critical point, the substance cannot exist in anything other than the gaseous state. The temperature component of the critical point for water is 705.2°F (374°C)—at 218 atm, or 218 times ordinary atmospheric pressure. For helium, however, critical temperature is just a few degrees above absolute zero. This is, in part, why helium is rarely seen in forms other than a gas.

**THE SUBLIMATION CURVE.** Another interesting phenomenon is the sublimation curve, or the line between solid and gas. At certain very low temperatures and pressures, a substance may experience sublimation, meaning that a gas turns into a solid, or a solid into a gas, without passing through a liquid stage.

A well-known example of sublimation occurs when "dry ice," made of carbon dioxide, vaporizes at temperatures above (–78.5°C). Carbon dioxide is exceptional, however, in that it experiences sublimation at relatively high pressures that occur in everyday life: for most substances, the sublimation point transpires at such a low pressure point that it is seldom witnessed outside of a laboratory.

**THE TRIPLE POINT.** The phenomenon known as the triple point shows how an ordinary substance such as water or carbon dioxide can actually be a liquid, solid, and vapor—all at once. Most people associate water as a gas or vapor (that is, steam) with very high temperatures. Yet, at a level far below normal atmospheric pressure, water can be a vapor at temperatures as low as –4°F (–20 °C). (All of the pressure values in the discussion of water at or near the triple point are far below atmospheric norms: the pressure at which water turns into a vapor at –4°F, for instance, is about 0.001 atm.)

Just as water can exist as a vapor at low temperatures and low pressures, it is also possible for water at temperatures below freezing to remain liquid. Under enough pressure, ice melts and is thereby transformed from a solid to a liquid, at temperatures below its normal freezing point. On the other hand, if the pressure of ice falls below a very low threshold, it will sublimate.

The phase diagram of water shows a line between the solid and liquid states that is almost, but not quite, exactly perpendicular to the x-axis. But in fact, it is a true fusion curve: it slopes slightly upward to the left, indicating that solid ice turns into water with an increase of pressure. Below a certain level of pressure is the vaporiza-

tion curve, and where the fusion curve intersects the vaporization curve, there is a place called the triple point. Just below freezing, in conditions equivalent to about 0.007 atm, water is a solid, liquid, and vapor all at once.

## Other States of Matter

**plasma.** Principal among states of matter other than solid, liquid, and gas is plasma, which is similar to gas. (The term "plasma," when referring to the state of matter, has nothing to do with the word as it is often used, in reference to blood plasma.) As with gas, plasma particles collide at high speeds—but in plasma the speeds are even greater, and the kinetic energy levels even higher.

The speed and energy of these collisions is directly related to the underlying property that distinguishes plasma from gas. So violent are the collisions between plasma particles that electrons are knocked away from their atoms. As a result, plasma does not have the atomic structure typical of a gas; rather, it is composed of positive ions and electrons. Plasma particles are thus electrically charged, and therefore greatly influenced by electric and magnetic fields.

Formed at very high temperatures, plasma is found in stars. The reaction between plasma and atomic particles in the upper atmosphere is responsible for the aurora borealis, or "northern lights." Though found on Earth only in very small quantities, plasma—ubiquitous in other parts of the universe—may be the most plentiful of all the states of matter.

**quasi-states.** Among the quasi-states of matter discussed by scientists are several terms describing the structure in which particles are joined, rather than the attraction and relative movement of those particles. Thus "crystalline," "amorphous," and "glassy" are all terms to describe what may be individual states of matter; so too is "colloidal."

A colloid is a structure intermediate in size between a molecule and a visible particle, and it has a tendency to be dispersed in another medium—the way smoke, for instance, is dispersed in air. Brownian motion describes the behavior of most colloidal particles. When one sees dust floating in a ray of sunshine through a window, the light reflects off colloids in the dust, which are driven back and forth by motion in the air otherwise imperceptible to the human senses.

**dark matter.** The number of states or phases of matter is clearly not fixed, and it is quite possible that more will be discovered in outer space, if not on Earth. One intriguing candidate is called dark matter, so described because it neither reflects nor emits light, and is therefore invisible. In fact, luminous or visible matter may very well make up only a small fraction of the mass in the universe, with the rest being taken up by dark matter.

If dark matter is invisible, how do astronomers and physicists know it exists? By analyzing the gravitational force exerted on visible objects in such cases where there appears to be no visible object to account for that force. An example is the center of our galaxy, the Milky Way. It appears to be nothing more than a dark "halo," but in order to cause the entire galaxy to revolve around it—in the same way that planets revolve around the Sun, though on a vastly larger scale—it must contain a staggering quantity of invisible mass.

## The Bose-Einstein Condensate

Physicists at the Joint Institute of Laboratory Astrophysics in Boulder, Colorado, in 1995 revealed a highly interesting aspect of atomic behavior at temperatures approaching absolute zero. Some 70 years before, Einstein had predicted that, at extremely low temperatures, atoms would fuse to form one large "superatom." This hypothesized structure was dubbed the Bose-Einstein Condensate (BEC) after Einstein and Satyendranath Bose (1894-1974), an Indian physicist whose statistical methods contributed to the development of quantum theory.

Cooling about 2,000 atoms of the element rubidium to a temperature just 170 billionths of a degree Celsius above absolute zero, the physicists succeeded in creating an atom 100 micrometers across—still incredibly small, but vast in comparison to an ordinary atom. The superatom, which lasted for about 15 seconds, cooled down all the way to just 20 billionths of a degree above absolute zero. The Colorado physicists won the Nobel Prize in physics in 1997 for their work.

In 1999, researchers in a lab at Harvard University also created a superatom of BEC, and used it to slow light to just 38 MPH (61.2 km/h)—about 0.02% of its ordinary speed.

Dubbed a "new" form of matter, the BEC may lead to a greater understanding of quantum mechanics, and may aid in the design of smaller, more powerful computer chips.

## SOME UNUSUAL PHASE TRANSITIONS

At places throughout this essay, references have been made variously to "phases" and "states" of matter. This is not intended to confuse, but rather to emphasize a particular point. Solids, liquids, and gases are referred to as "phases" because many (though far from all) substances on Earth regularly move from one phase to another.

There is absolutely nothing incorrect in referring to "states of matter." But "phases of matter" is used in the present context as a means of emphasizing the fact that substances, at the appropriate temperature and pressure, can be solid, liquid, or gas. The phases of matter, in fact, can be likened to the phases of a person's life: infancy, babyhood, childhood, adolescence, adulthood, old age. The transition between these stages is indefinite, yet it is easy enough to say when a person is at a certain stage.

**LIQUID CRYSTALS.** A liquid crystal is a substance that, over a specific range of temperature, displays properties both of a liquid and a solid. Below this temperature range, it is unquestionably a solid, and above this range it is just as certainly a liquid. In between, however, liquid crystals exhibit a strange solid-liquid behavior: like a liquid, their particles flow, but like a solid, their molecules maintain specific crystalline arrangements.

The cholesteric class of liquid crystals is so named because the spiral patterns of light through the crystal are similar to those which appear in cholesterols. Depending on the physical properties of a cholesteric liquid crystal, only certain colors may be reflected. The response of liquid crystals to light makes them useful in liquid crystal displays (LCDs) found on laptop computer screens, camcorder views, and in other applications.

**LIQUEFACTION OF GASES.** One interesting and useful application of phase change is the liquefaction of gases, or the change of gas into liquid by the reduction in its molecular energy levels. Liquefied natural gas (LNG) and liquefied petroleum gas (LPG), the latter a mixture of by-products obtained from petroleum and natural gas, are among the examples of liquefied gas in daily use. In both cases, the volume of the liquefied gas is far less than it would be if the gas were in a vaporized state, thus enabling ease and economy of transport.

Liquefied gases are used as heating fuel for motor homes, boats, and homes or cabins in remote areas. Other applications of liquefied gases include liquefied oxygen and hydrogen in rocket engines; liquefied oxygen and petroleum used in welding; and a combination of liquefied oxygen and nitrogen used in aqualung devices. The properties of liquefied gases figure heavily in the science of producing and studying low-temperature environments. In addition, liquefied helium is used in studying the behavior of matter at temperatures close to absolute zero.

**COAL GASIFICATION.** Coal gasification, as one might discern from the name, is the conversion of coal to gas. Developed before World War II, it fell out of favor after the war, due to the lower cost of oil and natural gas. However, increasingly stringent environmental regulations imposed by the federal government on industry during the 1970s, combined with a growing concern for the environment on the part of the populace as a whole, led to a resurgence of interest in coal gasification.

Though widely used as a fuel in power plants, coal, when burned by ordinary means, generates enormous air pollution. Coal gasification, on the other hand, makes it possible to burn "clean" coal. Gasification involves a number of chemical reactions, some exothermic or heat-releasing, and some endothermic or heat-absorbing. At one point, carbon monoxide is released in an exothermic reaction, then mixed with hydrogen released from the coal to create a second exothermic reaction. The energy discharged in these first two reactions is used to initiate a third, endothermic, reaction.

The finished product of coal gasification is a mixture containing carbon monoxide, methane, hydrogen, and other substances, and this—rather than ordinary coal—is burned as a fuel. The composition of the gases varies according to the process used. Products range from coal synthesis gas and medium-Btu gas (both composed of car-

## KEY TERMS

**ABSOLUTE ZERO:** The temperature, defined as 0K on the Kelvin scale, at which the motion of molecules in a solid virtually ceases. Absolute zero is equal to –459.67°F (–273.15°C).

**ATOM:** The smallest particle of an element that retains the chemical and physical properties of the element. An atom can exist either alone or in combination with other atoms in a molecule. Atoms are made up of protons, neutrons, and electrons. An atom that loses or gains one or more electrons, and thus has a net charge, is an ion. Atoms that have the same number of protons—that is, are of the same element—but differ in number of neutrons, are known as isotopes.

**ATOMIC MASS UNIT:** An SI unit (abbreviated amu), equal to $1.66 \cdot 10^{-24}$ 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.

**ATOMIC SOLID:** A form of crystalline solid in which atoms of one element bond to one another. Examples include diamonds (made of pure carbon), silicon, and all metals.

**AVERAGE ATOMIC MASS:** A figure used by chemists to specify the mass—in atomic mass units—of the average atom in a large sample. If a substance is a compound, the average atomic mass of all atoms in a molecule of that substance must be added together to yield the average molecular mass of that substance.

**AVOGADRO'S NUMBER:** A figure, named after Italian physicist Amedeo Avogadro (1776-1856), equal to $6.022137 \times 10^{23}$. Avogadro's number indicates the number of atoms, molecules, or other elementary particles in a mole.

**CHANGE OF PHASE:** The transition from one phase of matter to another.

**CRITICAL POINT:** A coordinate, plotted on a phase diagram, above which a substance cannot exist in anything other than the gaseous state. Located at a position of very high temperature and pressure, the critical point marks the termination of the vaporization curve.

**COMPOUND:** A substance made up of atoms of more than one element. These atoms are usually, but not always, joined in molecules.

**CRYSTALLINE SOLID:** A type of solid in which the constituent parts have a simple and definite geometric arrangement that is repeated in all directions. Types of crystalline solids include atomic solids, ionic solids, and molecular solids.

**ELEMENT:** A substance made up of only one kind of atom.

**ELECTRON:** A negatively charged particle in an atom. Electrons, which spin around the protons and neutrons that make up the atom's nucleus, constitute a very small portion of the atom's mass. In most atoms, the number of electrons and protons is the same, thus canceling out one another. When an atom loses one or more electrons, however—thus becoming an ion—it acquires a net electric charge.

## KEY TERMS CONTINUED

**ENERGY:** The ability to accomplish work—that is, the exertion of force over a given distance to displace or move an object.

**FUSION CURVE:** The boundary between solid and liquid for any given substance as plotted on a phase diagram.

**GAS:** A phase of matter in which molecules move at high speeds, and therefore exert little or no attraction toward one another.

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

**IONIC SOLID:** A form of crystalline solid that contains ions. When mixed with a solvent such as water, ions from table salt—an example of an ionic solid—move freely throughout the solution, making it possible to conduct an electric current.

**ISOTOPES:** Atoms that have an equal number of protons, and hence are of the same element, but differ in their number of neutrons.

**KINETIC ENERGY:** The energy that an object possesses by virtue of its movement.

**LIQUID:** A phase of matter in which molecules move at moderate speeds, and therefore exert moderate attractions toward one another.

**MATTER:** Physical substance that occupies space, has mass, is composed of atoms (or in the case of subatomic particles, is part of an atom), and is convertible to energy.

**MOLAR HEAT OF FUSION:** The amount of energy required to melt 1 mole of a solid substance.

**MOLAR HEAT OF VAPORIZATION:** The amount of energy required to turn 1 mole of a liquid into a gas. Because gases possess much more energy than liquids or solids, molar heat of vaporization is usually much higher than molar heat of fusion.

**MOLAR MASS:** The mass, in grams, of 1 mole of a given substance. The value in grams of molar mass is always equal to the value, in atomic mass units, of the average atomic mass of that substance: thus carbon has a molar mass of 12.01 g, and an average atomic mass of 12.01 amu.

**MOLE:** The SI fundamental unit for "amount of substance." A mole is, generally speaking, Avogadro's number of atoms, molecules, or other elementary particles; however, in the more precise SI definition, a mole is equal to the number of carbon atoms in 12.01 g of carbon.

**MOLECULAR SOLID:** A form of crystalline solid in which the molecules have a neutral electric charge, meaning that there are no ions present as there are in an ionic solid. Table sugar (sucrose) is an example of a molecular solid. When mixed with a solvent such as water, the resulting solution does not conduct electricity.

**MOLECULE:** A group of atoms, usually of more than one element, joined in a structure.

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

## KEY TERMS CONTINUED

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

**PHASE DIAGRAM:** A chart, plotted for any particular substance, identifying the particular phase of matter for that substance at a given temperature and pressure level. A phase diagram usually shows temperature along the x-axis, and pressure along the y-axis.

**PHASES OF MATTER:** The various forms of material substance (matter), which are defined primarily in terms of the behavior exhibited by their atomic or molecular structures. On Earth, three principal phases of matter exist, namely solid, liquid, and gas. Other forms of matter include plasma.

**PLASMA:** One of the phases of matter, closely related to gas. Plasma is found primarily in stars. Containing neither atoms nor molecules, plasma is made up of electrons and positive ions.

**PROTON:** A positively charged particle in an atom. Protons and neutrons, which together form the nucleus around which electrons spin, have approximately the same mass—a mass that is many times greater than that of an electron. The number of protons in the nucleus of an atom is the atomic number of an element.

**SOLID:** A phase of matter in which molecules move slowly relative to one another, and therefore exert strong attractions toward one another.

**SUBLIMATION CURVE:** The boundary between solid and gas for any given substance, as plotted on a phase diagram.

**SYSTEM:** In chemistry and other sciences, the term "system" usually refers to any set of interactions isolated from the rest of the universe. Anything outside of the system, including all factors and forces irrelevant to a discussion of that system, is known as the environment.

**THERMAL ENERGY:** "Heat" energy, a form of kinetic energy produced by the relative motion of atoms or molecules. The greater the movement of these particles, the greater the thermal energy.

**VAPORIZATION CURVE:** The boundary between liquid and gas for any given substance as plotted on a phase diagram.

bon monoxide and hydrogen, though combined in different forms) to substitute natural gas, which consists primarily of methane.

Not only does coal gasification produce a clean-burning product, but it does so without the high costs associated with flue-gas desulfurization systems. The latter, often called "scrubbers," were originally recommended by the federal government to industry, but companies discovered that coal gasification could produce the same results for much less money. In addition, the waste products from coal gasification can be used for other purposes. At the Cool Water Integrated Gasification Combined Cycle Plant, established in Barstow, California, in 1984, sulfur obtained from the reduction of sulfur dioxide is sold off for about $100 a ton.

### The Chemical Dimension to Changes of Phase

Throughout much of this essay, we have discussed changes of phase primarily in physical terms; yet clearly these changes play a significant role in chemistry. Furthermore, coal gasification

serves to illustrate the impact chemical processes can have on changes of state.

Much earlier, figures were given for the melting points of copper, water, and helium, and these were compared with the average atomic mass of each. Those figures, again, are:

*Average Atomic Mass and Melting Points of a Sample Gas, Liquid, and Solid*

- Helium: 4.003 amu; –457.6°F (–210°C)
- Water: 40.304 amu 32°F (0°C)
- Copper: 63.55 amu; 1,985°F (1,085°C).

Something seems a bit strange about those comparisons: specifically, the differences in melting point appear to be much more dramatic than the differences in average atomic mass. Clearly, another factor is at work—a factor that relates to the difference in the attractions between molecules in each. Although the differences between solids, liquids, and gases are generally physical, the one described here—a difference between substances—is clearly chemical in nature.

To discuss this in the detail it deserves would require a lengthy digression on the chemical dimensions of intermolecular attraction. Nonetheless, it is possible here to offer at least a cursory answer to the question raised by these striking differences in response to temperature.

## Dipoles, Electron Seas, and London Dispersion

Water molecules are polar, meaning that one area of a water molecule is positively charged, while another area has a negative charge. Thus the positive side of one molecule is drawn to the negative side of another, and vice versa, which gives water a much stronger intermolecular bond than, for instance, oil, in which the positive and negative charges are evenly distributed throughout the molecule.

Yet the intermolecular attraction between the dipoles (as they are called) in water is not nearly as strong as the bond that holds together a metal. Particles in copper or other metals "float" in a tightly packed "sea" of highly mobile electrons, which provide a bond that is powerful, yet lacking in a firm directional orientation. Thus metals are both strong and highly malleable (that is, they can be hammered very flat without breaking.)

Water, of course, appears most often as a liquid, and copper as a solid, precisely because water has a very high boiling point (the point at which it becomes a vapor) and copper has a very high melting point. But consider helium, which has the lowest freezing point of any element: just above absolute zero. Even then, a pressure equal to 25 times that of normal atmospheric pressure is required to push it past the freezing point.

Helium and other Group 8 or Group 18 elements, as well as non-polar molecules such as oils, are bonded by what is called London dispersion forces. The latter, as its name suggests, tends to keep molecules dispersed, and induces instantaneous dipoles when most of the electrons happen to be on one side of an atom. Of course, this happens only for an infinitesimal fraction of time, but it serves to create a weak attraction. Only at very low temperatures do London dispersion forces become strong enough to result in the formation of a solid.

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# GASES

## CONCEPT

The number of elements that appear ordinarily in the form of a gas is relatively small: oxygen, hydrogen, fluorine, and chlorine in the halogen "family"; and a handful of others, most notably the noble gases in Group 8 of the periodic table. Yet many substances can exist in the form of a gas, depending on the relative attraction and motion of molecules in that substance. A simple example, of course, is water, or $H_2O$, which, though it appears as a liquid at room temperature, begins to vaporize and turn into steam at 212°F (100°C). In general, gases respond more dramatically to changes in pressure and temperature than do most other types of matter, and this allows scientists to predict gas behaviors under certain conditions. These predictions can explain mundane occurrences, such as the fact that an open can of soda will soon lose its fizz, but they also apply to more dramatic, life-and-death situations.

## HOW IT WORKS

### Molecular Motion and Phases of Matter

On Earth, three principal phases or states of matter exist: solid, liquid, and gas. The differences between these three are, on the surface at least, easily perceivable. Clearly water is a liquid, just as ice is a solid and steam a vapor or gas. Yet the ways in which various substances convert between phases are often complex, as are the interrelations between these phases. Ultimately, understanding of the phases depends on an awareness of what takes place at the molecular level.

All molecules are in motion, and the rate of that motion determines the attraction between them. The movement of molecules generates kinetic energy, or the energy of movement, which is manifested as thermal energy. In everyday language, thermal energy is what people mean when they say "heat"; but in scientific terms, heat has a different definition.

The force that attracts atoms to atoms, or molecules to molecules, is not the same as gravitational force, which holds the Moon in orbit around Earth, Earth in orbit around the Sun, and so on. By contrast, the force of interatomic and intermolecular attraction is electromagnetic. Just as the north pole of a magnet is attracted to the south pole of another magnet and repelled by that other magnet's north pole, so positive electric charges are attracted to negative charges, and negatives to positives. (In fact, electricity and magnetism are both manifestations of an electromagnetic interaction.)

The electromagnetic attractions between molecules are much more complex than this explanation makes it seem, and they play a highly significant role in chemical bonding. In simple terms, however, one can say that the greater the rate of motion for the molecules in relation to one another, the less the attraction between molecules. In addition, the kinetic energy, and hence the thermal energy, is greater in a substance whose molecules are relatively free to move.

When the molecules in a material move slowly in relation to one another, they exert a strong attraction, and the material is called a solid. Molecules of liquid, by contrast, move at

| STATE | VOLUME FORM SHAPE COMPRESSIBILITY | ARRANGEMENT AND CLOSENESS OF PARTICLES | MOTION OF PARTICLES | ATTRACTION BETWEEN PARTICLES | BOILING POINT |
|---|---|---|---|---|---|
| GAS | No definite volume, form or shape Compressible | Random Far apart | Fast | Little to None | Lower than Room Temperature |
| LIQUID | Has a definite volume, but no definite form or shape Non compressive tendency | Random Close | Moderate | Moderate | Higher than Room Temperature |
| SOLID | Definite volume, has own shape or form Non compressible | Definite Close | Slow | Strong | Much higher than Room Temperature |

A comparison of gas, liquid, and solid states.

moderate speeds and exert a moderate attraction. A material substance whose molecules move at high speeds, and therefore exert little or no attraction, is known as a gas.

## Comparison of Gases to Other Phases of Matter

**WATER AND AIR COMPARED.** Gases respond to changes in pressure and temperature in a manner remarkably different from that of solids or liquids. Consider the behavior of liquid water as compared with air—a combination of oxygen ($O_2$), nitrogen ($N_2$), and other gases—in response to experiments involving changes in pressure and temperature.

In the first experiment, both samples are subjected to an increase in pressure from 1 atm (that is, normal atmospheric pressure at sea level) to 2 atm. In the second, both experience an increase in temperature from 32°F (0°C) to 212°F (100°C). The differences in the responses of water and air are striking.

A sample of water that experiences an increase in pressure from 1 to 2 atm will decrease in volume by less than 0.01%, while a temperature increase from the freezing point to the boiling point will result in only a 2% increase in volume. For air, however, an equivalent pressure increase will decrease the volume by a whopping 50%, and an equivalent temperature increase results in a volume increase of 37%.

Air and other gases, by definition, have a boiling point below room temperature. If they did not boil and thus become gas well below ordinary temperatures, they would not be described as substances that are in the gaseous state in most circumstances. The boiling point of water, of course, is higher than room temperature, and that of solids is much higher.

**THE ARRANGEMENT OF PARTICLES.** Solids possess a definite volume and a definite shape, and are relatively noncompressible: for instance, if one applies extreme pressure to a steel plate, it will bend, but not much. Liquids have a definite volume, but no definite shape, and tend to be noncompressible. Gases, on the other hand, possess no definite volume or shape, and are highly compressible.

At the molecular level, particles of solids tend to be definite in their arrangement and close in proximity—indeed, part of what makes a solid "solid," in the everyday meaning of that term, is the fact that its constituent parts are basically immovable. Liquid molecules, too, are close in proximity, though random in arrangement. Gas



The divers pictured here have ascended from a sunken ship and have stopped at the 10-ft (3-meter) decompression level to avoid getting decompression sickness, better known as the "bends." *(Jonathan Blair/Corbis. Reproduced by permission)*

molecules are random in arrangement, but tend to be more widely spaced than liquid molecules.

## Pressure

There are a number of statements, collectively known as the "gas laws," that describe and predict the behavior of gases in response to changes in temperature, pressure, and volume. Temperature and volume are discussed elsewhere in this book. However, the subject of pressure requires some attention before we can continue with a discussion of the gas laws.

When a force is applied perpendicular to a surface area, it exerts pressure on that surface. Hence the formula for pressure is $p = F/A$, where $p$ is pressure, $F$ force, and $A$ the area over which the force is applied. The greater the force, and the smaller the area of application, the greater the pressure; conversely, an increase in area—even without a reduction in force—reduces the overall pressure.

Pressure is measured by a number of units in the English and SI systems. Because $p = F/A$, all units of pressure represent some ratio of force to surface area.

**UNITS OF PRESSURE.** The principal SI unit of pressure is called a pascal (Pa), or 1 $N/m^2$. It is named for French mathematician and physicist Blaise Pascal (1623-1662), who is credited with Pascal's principle. The latter holds that the external pressure applied on a fluid—which, in the physical sciences, can mean either a gas or a liquid—is transmitted uniformly throughout the entire body of that fluid.

A newton (N), the SI unit of force, is equal to the force required to accelerate 1 kg of mass at a rate of 1 $m/sec^2$. Thus a Pascal is the pressure of 1 newton over a surface area of 1 $m^2$. In the English or British system, pressure is measured in terms of pounds per square inch, abbreviated as $lbs./in^2$. This is equal to $6.89 \cdot 10^3$ Pa, or 6,890 Pa.

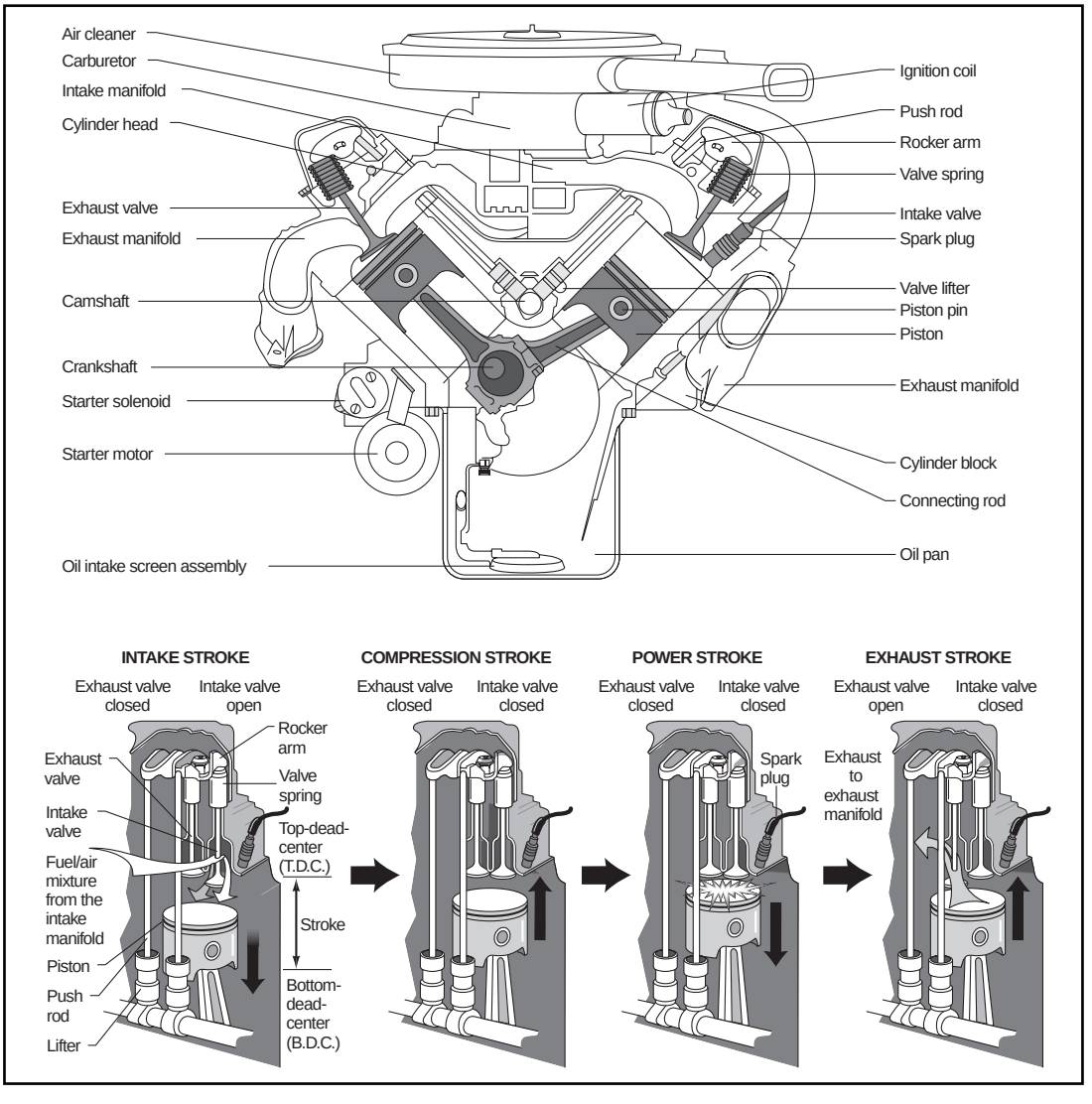
Another important measure of pressure is the atmosphere (atm), which is the average pressure exerted by air at sea level. In English units, this is equal to 14.7 $lb/in^2$, and in SI units, to $1.013 \cdot 10^5$ Pa.

There are two other specialized units of pressure measurement in the SI system: the bar, equal to $10^5$ Pa, and the torr, equal to 133 Pa. Meteorologists, scientists who study weather patterns, use the millibar (mb), which, as its name implies, is equal to 0.001 bars. At sea level, atmospheric pressure is approximately 1,013 mb.

The torr, also known as the millimeter of mercury (mm Hg), is the amount of pressure required to raise a column of mercury (chemical symbol Hg) by 1 mm. It is named for Italian physicist Evangelista Torricelli (1608-1647), who invented the barometer, an instrument for measuring atmospheric pressure.

**THE BAROMETER.** The barometer constructed by Torricelli in 1643 consisted of a long glass tube filled with mercury. The tube was open at one end, and turned upside down into a dish containing more mercury: the open end was submerged in mercury, while the closed end at the top constituted a vacuum—that is, an area devoid of matter, including air.

The pressure of the surrounding air pushed down on the surface of the mercury in the bowl, while the vacuum at the top of the tube provided an area of virtually no pressure into which the mercury could rise. Thus the height to which the




The major components of an internal combustion engine (top), and the four strokes of its combustion sequence (bottom).

mercury rose in the glass tube represented normal air pressure (that is, 1 atm.) Torricelli discovered that at standard atmospheric pressure, the column of mercury rose to 760 mm (29.92 in).

The value of 1 atm was thus established as equal to the pressure exerted on a column of mercury 760 mm high at a temperature of 0°C (32°F). In time, Torricelli's invention became a fixture both of scientific laboratories and of households. Since changes in atmospheric pressure have an effect on weather patterns, many home indoor-outdoor thermometers today also include a barometer.

## REAL-LIFE APPLICATIONS

### Introduction to the Gas Laws

English chemist Robert Boyle (1627-1691), who made a number of important contributions to chemistry—including his definition and identification of elements—seems to have been influenced by Torricelli. If so, this is an interesting example of ideas passing from one great thinker to another: Torricelli, a student of Galileo Galilei (1564-1642), was no doubt influenced by Galileo's thermoscope.

Like Torricelli, Boyle conducted tests involving the introduction of mercury to a tube closed

at the other end. The tube Boyle used was shaped like the letter J, and it was so long that he had to use the multi-story foyer of his house as a laboratory. At the tip of the curved bottom was an area of trapped gas, and into the top of the tube, Boyle introduced increasing quantities of mercury. He found that the greater the volume of mercury, the greater the pressure on the gas, and the less the volume of gas at the end of the tube. As a result, he formulated the gas law associated with his name.

The gas laws are not a set of government regulations concerning use of heating fuel; rather, they are a series of statements concerning the behavior of gases in response to changes in temperature, pressure, and volume. These were derived, beginning with Boyle's law, during the seventeenth, eighteenth, and nineteenth centuries by scientists whose work is commemorated through the association of their names with the laws they discovered. In addition to Boyle, these men include fellow English chemists John Dalton (1766-1844) and William Henry (1774-1836); French physicists and chemists J. A. C. Charles (1746-1823) and Joseph Gay-Lussac (1778-1850); and Italian physicist Amedeo Avogadro (1776-1856).

There is a close relationship between Boyle's, Charles's, and Gay-Lussac's laws. All of these treat one of three parameters—temperature, pressure, or volume—as fixed quantities in order to explain the relationship between the other two variables. Avogadro's law treats two of the parameters as fixed, thereby establishing a relationship between volume and the number of molecules in a gas. The ideal gas law sums up these four laws, and the kinetic theory of gases constitutes an attempt to predict the behavior of gases based on these laws. Finally, Dalton's and Henry's laws both relate to partial pressure of gases.

## Boyle's, Charles's, and Gay-Lussac's Laws

**Boyle's and Charles's laws.** Boyle's law holds that in isothermal conditions (that is, a situation in which temperature is kept constant), an inverse relationship exists between the volume and pressure of a gas. (An inverse relationship is a situation involving two variables, in which one of the two increases in direct proportion to the decrease in the other.) In this case, the greater the pressure, the less the volume and vice versa. Therefore, the product of the volume multiplied by the pressure remains constant in all circumstances.

Charles's law also yields a constant, but in this case the temperature and volume are allowed to vary under isobarometric conditions—that is, a situation in which the pressure remains the same. As gas heats up, its volume increases, and when it cools down, its volume reduces accordingly. Hence, Charles established that the ratio of temperature to volume is constant.

**Absolute temperature.** In about 1787, Charles made an interesting discovery: that at 0°C (32°F), the volume of gas at constant pressure drops by 1/273 for every Celsius degree drop in temperature. This seemed to suggest that the gas would simply disappear if cooled to -273°C (-459.4°F), which, of course, made no sense. In any case, the gas would most likely become first a liquid, and then a solid, long before it reached that temperature.

The man who solved the quandary raised by Charles's discovery was born a year after Charles died. He was William Thomson, Lord Kelvin (1824-1907); in 1848, he put forward the suggestion that it was molecular translational energy—the energy generated by molecules in motion—and not volume, that would become zero at -273°C. He went on to establish what came to be known as the Kelvin scale of absolute temperature.

Sometimes known as the absolute temperature scale, the Kelvin scale is based not on the freezing point of water, but on absolute zero—the temperature at which molecular motion comes to a virtual stop. This is -273.15°C (-459.67°F). In the Kelvin scale, which uses neither the term nor the symbol for "degree," absolute zero is designated as 0K.

Scientists prefer the Kelvin scale to the Celsius, and certainly to the Fahrenheit, scales. If the Kelvin temperature of an object is doubled, its average molecular translational energy has doubled as well. The same cannot be said if the temperature were doubled from, say, 10°C to 20°C, or from 40°F to 80°F, since neither the Celsius nor the Fahrenheit scale is based on absolute zero.

**Gay-Lussac's law.** From Boyle's and Charles's law, a pattern should be emerging: both treat one parameter (temperature in Boyle's, pressure in Charles's) as unvarying, while

two other factors are treated as variables. Both, in turn, yield relationships between the two variables: in Boyle's law, pressure and volume are inversely related, whereas in Charles's law, temperature and volume are directly related.

In Gay-Lussac's law, a third parameter, volume, is treated as a constant, and the result is a constant ratio between the variables of pressure and temperature. According to Gay-Lussac's law, the pressure of a gas is directly related to its absolute temperature.

## Avogadro's Law

Gay-Lussac also discovered that the ratio in which gases combine to form compounds can be expressed in whole numbers: for instance, water is composed of one part oxygen and two parts hydrogen. In the language of modern chemistry, this is expressed as a relationship between molecules and atoms: one molecule of water contains one oxygen atom and two hydrogen atoms.

In the early nineteenth century, however, scientists had yet to recognize a meaningful distinction between atoms and molecules, and Avogadro was the first to achieve an understanding of the difference. Intrigued by the whole-number relationship discovered by Gay-Lussac, Avogadro reasoned that one liter of any gas must contain the same number of particles as a liter of another gas. He further maintained that gas consists of particles—which he called molecules—that in turn consist of one or more smaller particles.

In order to discuss the behavior of molecules, Avogadro suggested the use of a large quantity as a basic unit, since molecules themselves are very small. Avogadro himself did not calculate the number of molecules that should be used for these comparisons, but when that number was later calculated, it received the name "Avogadro's number" in honor of the man who introduced the idea of the molecule. Equal to $6.022137 \cdot 10^{23}$, Avogadro's number designates the quantity of atoms or molecules (depending on whether the substance in question is an element or a compound) in a mole.

Today the mole (abbreviated mol), the SI unit for "amount of substance," is defined precisely as the number of carbon atoms in 12.01 g of carbon. The term "mole" can be used in the same way we use the word "dozen." Just as "a dozen" can refer to twelve cakes or twelve chickens, so "mole" always describes the same number of molecules. The ratio of mass between a mole of Element A and Element B, or Compound A and Compound B, is the same as the ratio between the mass of Atom A and Atom B, or Molecule A and Molecule B. Avogadro's law describes the connection between gas volume and number of moles. According to Avogadro's law, if the volume of gas is increased under isothermal and isobarometric conditions, the number of moles also increases. The ratio between volume and number of moles is therefore a constant.

## The Ideal Gas Law

Once again, it is easy to see how Avogadro's law can be related to the laws discussed earlier. Like the other three, this one involves the parameters of temperature, pressure, and volume, but it also introduces a fourth—quantity of molecules (that is, number of moles). In fact, all the laws so far described are brought together in what is known as the ideal gas law, sometimes called the combined gas law.

The ideal gas law can be stated as a formula, pV = nRT, where p stands for pressure, V for volume, n for number of moles, and T for temperature. R is known as the universal gas constant, a figure equal to 0.0821 atm • liter/mole • K. (Like most figures in chemistry, this one is best expressed in metric rather than English units.)

Given the equation $pV = nRT$ and the fact that R is a constant, it is possible to find the value of any one variable—pressure, volume, number of moles, or temperature—as long as one knows the value of the other three. The ideal gas law also makes it possible to discern certain relationships: thus, if a gas is in a relatively cool state, the product of its pressure and volume is proportionately low; and if heated, its pressure and volume product increases correspondingly.

## The Kinetic Theory of Gases

From the preceding gas laws, a set of propositions known collectively as the kinetic theory of gases has been derived. Collectively, these put forth the proposition that a gas consists of numerous molecules, relatively far apart in space, which interact by colliding. These collisions are responsible for the production of thermal energy, because when the velocity of the molecules increases—as it does after collision—the temperature increases as well.

There are five basic postulates to the kinetic theory of gases:

- 1. Gases consist of tiny molecular or atomic particles.
- 2. The proportion between the size of these particles and the distances between them is so small that the individual particles can be assumed to have negligible volume.
- 3. These particles experience continual random motion. When placed in a container, their collisions with the walls of the container constitute the pressure exerted by the gas.
- 4. The particles neither attract nor repel one another.
- 5. The average kinetic energy of the particles in a gas is directly related to absolute temperature.

These observations may appear to resemble statements made earlier concerning the differences between gases, liquids, and solids in terms of molecular behavior. If so, that is no accident: the kinetic theory constitutes a generally accepted explanation for the reasons why gases behave as they do. Kinetic theories do not work as well for explaining the behaviors of solids and liquids; nonetheless, they do go a long way toward identifying the molecular properties inherent in the various phases of matter.

## Laws of Partial Pressure

In addition to all the gas laws so far discussed, two laws address the subject of partial pressure. When two or more gases are present in a container, partial pressure is the pressure that one of them exerts if it alone is in the container.

Dalton's law of partial pressure states that the total pressure of a gas is equal to the sum of its partial pressures. As noted earlier, air is composed mostly of nitrogen and oxygen. Along with these are small components, carbon dioxide, and gases collectively known as the rare or noble gases: argon, helium, krypton, neon, radon, and xenon. Hence, the total pressure of a given quantity of air is equal to the sum of the pressures exerted by each of these gases.

Henry's law states that the amount of gas dissolved in a liquid is directly proportional to the partial pressure of the gas above the surface of the solution. This applies only to gases such as oxygen and hydrogen that do not react chemically to liquids. On the other hand, hydrochloric acid will ionize when introduced to water: one or more of its electrons will be removed, and its atoms will convert to ions, which are either positive or negative in charge.

## Applications of Dalton's and Henry's Laws

**PARTIAL PRESSURE: A MATTER OF LIFE AND POSSIBLE DEATH FOR SCUBA DIVERS.** The gas laws are not just a series of abstract statements. Certainly, they do concern the behavior of ideal as opposed to real gases. Like all scientific models, they remove from the equation all outside factors, and treat specific properties in isolation. Yet, the behaviors of the ideal gases described in the gas laws provide a key to understanding the activities of real gases in the real world. For instance, the concept of partial pressure helps scuba divers avoid a possibly fatal sickness.

Imagine what would happen if a substance were to bubble out of one's blood like carbon dioxide bubbling out of a soda can, as described below. This is exactly what can happen to an undersea diver who returns to the surface too quickly: nitrogen rises up within the body, producing decompression sickness—known colloquially as "the bends." This condition may manifest as itching and other skin problems, joint pain, choking, blindness, seizures, unconsciousness, permanent neurological defects such as paraplegia, and possibly even death.

If a scuba diver descending to a depth of 150 ft (45.72 m) or more were to use ordinary air in his or her tanks, the results would be disastrous. The high pressure exerted by the water at such depths creates a high pressure on the air in the tank, meaning a high partial pressure on the nitrogen component in the air. The result would be a high concentration of nitrogen in the blood, and hence the bends.

Instead, divers use a mixture of helium and oxygen. Helium gas does not dissolve well in blood, and thus it is safer for a diver to inhale this oxygen-helium mixture. At the same time, the oxygen exerts the same pressure that it would normally—in other words, it operates in accordance with Dalton's observations concerning partial pressure.

**OPENING A SODA CAN.** Inside a can or bottle of carbonated soda is carbon diox-

ide gas ($CO_2$), most of which is dissolved in the drink itself. But some of it is in the space (sometimes referred to as "head space") that makes up the difference between the volume of the soft drink and the volume of the container.

At the bottling plant, the soda manufacturer adds high-pressure carbon dioxide ($CO_2$) to the head space in order to ensure that more $CO_2$ will be absorbed into the soda itself. This is in accordance with Henry's law: the amount of gas (in this case $CO_2$) dissolved in the liquid (soda) is directly proportional to the partial pressure of the gas above the surface of the solution—that is, the $CO_2$ in the head space. The higher the pressure of the $CO_2$ in the head space, the greater the amount of $CO_2$ in the drink itself; and the greater the $CO_2$ in the drink, the greater the "fizz" of the soda.

Once the container is opened, the pressure in the head space drops dramatically. Once again, Henry's law indicates that this drop in pressure will be reflected by a corresponding drop in the amount of $CO_2$ dissolved in the soda. Over a period of time, the soda will release that gas, and eventually, it will go "flat."

**FIRE EXTINGUISHERS.** A fire extinguisher consists of a long cylinder with an operating lever at the top. Inside the cylinder is a tube of carbon dioxide surrounded by a quantity of water, which creates pressure around the $CO_2$ tube. A siphon tube runs vertically along the length of the extinguisher, with one opening in the water near the bottom. The other end opens in a chamber containing a spring mechanism attached to a release valve in the $CO_2$ tube.

The water and the $CO_2$ do not fill the entire cylinder: as with the soda can, there is "head space," an area filled with air. When the operating lever is depressed, it activates the spring mechanism, which pierces the release valve at the top of the $CO_2$ tube. When the valve opens, the $CO_2$ spills out in the "head space," exerting pressure on the water. This high-pressure mixture of water and carbon dioxide goes rushing out of the siphon tube, which was opened when the release valve was depressed. All of this happens, of course, in a fraction of a second—plenty of time to put out the fire.

**AEROSOL CANS.** Aerosol cans are similar in structure to fire extinguishers, though with one important difference. As with the fire extinguisher, an aerosol can includes a nozzle that depresses a spring mechanism, which in turn allows fluid to escape through a tube. But instead of a gas cartridge surrounded by water, most of the can's interior is made up of the product (for instance, deodorant), mixed with a liquid propellant.

The "head space" of the aerosol can is filled with highly pressurized propellant in gas form, and, in accordance with Henry's law, a corresponding proportion of this propellant is dissolved in the product itself. When the nozzle is depressed, the pressure of the propellant forces the product out through the nozzle.

A propellant, as its name implies, propels the product itself through the spray nozzle when the nozzle is depressed. In the past, chlorofluorocarbons (CFCs)—manufactured compounds containing carbon, chlorine, and fluorine atoms—were the most widely used form of propellant. Concerns over the harmful effects of CFCs on the environment, however, has led to the development of alternative propellants, most notably hydrochlorofluorocarbons (HCFCs), CFC-like compounds that also contain hydrogen atoms.

## Applications of Boyle's, Charles's, and Gay-Lussac's Laws

**WHEN THE TEMPERATURE CHANGES.** A number of interesting results occur when gases experience a change in temperature, some of them unfortunate and some potentially lethal. In these instances, it is possible to see the gas laws—particularly Boyle's and Charles's—at work.

There are numerous examples of the disastrous effects that result from an increase in the temperature of combustible gases, including natural gas and petroleum-based products. In addition, the pressure on the gases in aerosol cans makes the cans highly explosive—so much so that discarded cans at a city dump may explode on a hot summer day. Yet, there are other instances when heating a gas can produce positive effects.

A hot-air balloon, for instance, floats because the air inside it is not as dense than the air outside. According to Charles's law, heating a gas will increase its volume, and since gas molecules exert little attraction toward one another,

they tend to "spread out" even further with an increase of volume. This, in turn, creates a significant difference in density between the air in the balloon and the air outside, and as a result, the balloon floats.

Although heating a gas can be beneficial, cooling a gas is not always a wise idea. If someone were to put a bag of potato chips into a freezer, thinking this would preserve their flavor, he would be in for a disappointment. Much of what maintains the flavor of the chips is the pressurization of the bag, which ensures a consistent internal environment so that preservative chemicals, added during the manufacture of the chips, can keep them fresh. Placing the bag in the freezer causes a reduction in pressure, as per Gay-Lussac's law, and the bag ends up a limp version of its former self.

Propane tanks and tires offer an example of the pitfalls that may occur by either allowing a gas to heat up or cool down by too much. Because most propane tanks are made according to strict regulations, they are generally safe, but it is not entirely inconceivable that the extreme heat of a summer day could cause a defective tank to burst. An increase in temperature leads to an increase in pressure, in accordance with Gay-Lussac's law, and could lead to an explosion.

Because of the connection between heat and pressure, propane trucks on the highways during the summer are subjected to weight tests to ensure that they are not carrying too much gas. On the other hand, a drastic reduction in temperature could result in a loss in gas pressure. If a propane tank from Florida were transported by truck during the winter to northern Canada, the pressure is dramatically reduced by the time it reaches its destination.

**THE INTERNAL-COMBUSTION ENGINE.** In operating a car, we experience two applications of the gas laws. One of these is what makes the car run: the combustion of gases in the engine, which illustrates the interrelation of volume, pressure, and temperature expressed in the laws attributed to Boyle, Charles, and Gay-Lussac. The other is, fortunately, a less frequent phenomenon—but it can and does save lives. This is the operation of an airbag, which depends, in part, on the behaviors explained in Charles's law.

When the driver of a modern, fuel-injection automobile pushes down on the accelerator, this activates a throttle valve that sprays droplets of gasoline mixed with air into the engine. The mixture goes into the cylinder, where the piston moves up, compressing the gas and air. While the mixture is still at a high pressure, the electric spark plug produces a flash that ignites the gasoline-air mixture. The heat from this controlled explosion increases the volume of air, which forces the piston down into the cylinder. This opens an outlet valve, causing the piston to rise and release exhaust gases.

As the piston moves back down again, an inlet valve opens, bringing another burst of gasoline-air mixture into the chamber. The piston, whose downward stroke closed the inlet valve, now shoots back up, compressing the gas and air to repeat the cycle. The reactions of the gasoline and air to changes in pressure, temperature, and volume are what move the piston, which turns a crankshaft that causes the wheels to rotate.

**THE AIRBAG.** So much for moving—what about stopping? Most modern cars are equipped with an airbag, which reacts to sudden impact by inflating. This protects the driver and front-seat passenger, who, even if they are wearing seatbelts, may otherwise be thrown against the steering wheel or dashboard.

In order to perform its function properly, the airbag must deploy within 40 milliseconds (0.04 seconds) of impact. Not only that, but it has to begin deflating before the body hits it. If a person's body, moving forward at speeds typical in an automobile accident, were to smash against a fully inflated airbag, it would feel like hitting concrete—with all the expected results.

The airbag's sensor contains a steel ball attached to a permanent magnet or a stiff spring. The spring or magnet holds the ball in place through minor mishaps when an airbag is not warranted—for instance, if a car were simply to be "tapped" by another in a parking lot. But in a case of sudden deceleration, the magnet or spring releases the ball, sending it down a smooth bore. The ball flips a switch, turning on an electrical circuit. This in turn ignites a pellet of sodium azide, which fills the bag with nitrogen gas.

At this point, the highly pressurized nitrogen gas molecules begin escaping through vents. Thus, as the driver's or rider's body hits the airbag, the deflation of the bag is moving it in the same direction that the body is moving—only

## KEY TERMS

**ABSOLUTE TEMPERATURE:** Temperature in relation to absolute zero (-273.15°C or -459.67°F), as measured on the Kelvin scale. The Kelvin and Celsius scales are directly related; hence, Celsius temperatures can be converted to Kelvins (for which neither the word nor the symbol for "degree" are used) by adding 273.15.

**ATMOSPHERE:** A measure of pressure, abbreviated "atm" and equal to the average pressure exerted by air at sea level. In English units, this is equal to 14.7 $lb/in^2$, and in SI units, to 101,300 pascals.

**AVOGADRO'S LAW:** A statement, derived by the Italian physicist Amedeo Avogadro (1776-1856), which holds that as the volume of gas increases under isothermal and isobarometric conditions, the number of molecules (expressed in terms of mole number), increases as well. Thus, the ratio of volume to mole number is a constant.

**BAROMETER:** An instrument for measuring atmospheric pressure.

**BOYLE'S LAW:** A statement, derived by English chemist Robert Boyle (1627-1691), which holds that for gases in isothermal conditions, an inverse relationship exists between the volume and pressure of a gas. This means that the greater the pressure, the less the volume and vice versa, and therefore the product of pressure multiplied by volume yields a constant figure.

**CHARLES'S LAW:** A statement, derived by French physicist and chemist J. A. C. Charles (1746-1823), which holds that for gases in isobarometric conditions, the ratio between the volume and temperature of a gas is constant. This means that the greater the temperature, the greater the volume, and vice versa.

**DALTON'S LAW OF PARTIAL PRESSURE:** A statement, derived by the English chemist John Dalton (1766-1844), which holds that the total pressure of a gas is equal to the sum of its partial pressures—that is, the pressure exerted by each component of the gas mixture.

**GAS:** A phase of matter in which molecules move at high speeds, and therefore exert little or no attraction toward one another.

**GAS LAWS:** A series of statements concerning the behavior of gases in response to changes in temperature, pressure, and volume. The gas laws, developed by scientists during the seventeenth, eighteenth, and nineteenth centuries, include Avogadro's law, Boyle's law, Charles's law, Dalton's law of partial pressures, Gay-Lussac's law, and Henry's law. These are summed up in the ideal gas law. The kinetic theory of gases is based on observations garnered from these laws.

**GAY-LUSSAC'S LAW:** A statement, derived by French physicist and chemist Joseph Gay-Lussac (1778-1850), which holds that the pressure of a gas is directly related to its absolute temperature. Hence, the ratio of pressure to absolute temperature is a constant.

**HENRY'S LAW:** A statement, derived

## KEY TERMS CONTINUED

by English chemist William Henry (1774-1836), which holds that the amount of gas dissolved in a liquid is directly proportional to the partial pressure of the gas above the solution. This holds true only for gases, such as hydrogen and oxygen, which do not react chemically to liquids.

**IDEAL GAS LAW:** A proposition, also known as the combined gas law, which draws on all the gas laws. The ideal gas law can be expressed as the formula $pV = nRT$, where p stands for pressure, V for volume, n for number of moles, and T for temperature. R is known as the universal gas constant, a figure equal to 0.0821 atm • liter/mole • K.

**ISOTHERMAL:** Referring to a situation in which temperature is kept constant.

**ISOBAROMETRIC:** Referring to a situation in which pressure is kept constant.

**KINETIC ENERGY:** The energy that an object possesses by virtue of its motion.

**KINETIC THEORY OF GASES:** A set of propositions describing a gas as consisting of numerous molecules, relatively far apart in space, which interact by colliding. These collisions are responsible for the production of thermal energy, because when the velocity of the molecules increases—as it does after collision—the temperature increases as well.

**MILLIMETER OF MERCURY:** Another name for the torr, abbreviated mm Hg.

**MOLE:** The SI fundamental unit for "amount of substance." The quantity of molecules or atoms in a mole is, generally speaking, the same as Avogadro's number: $6.022137 \cdot 10^{23}$. However, in the more precise SI definition, a mole is equal to the number of carbon atoms in 12.01 g of carbon.

**PARTIAL PRESSURE:** When two or more gases are present in a container, partial pressure is the pressure that one of them exerts if it alone is in the container. Dalton's law of partial pressure and Henry's law relate to the partial pressure of gases.

**PASCAL:** The principle SI or metric unit of pressure, abbreviated "Pa" and equal to 1 $N/m^2$.

**PRESSURE:** The ratio of force to surface area, when force is applied in a direction perpendicular to that surface.

**THERMAL ENERGY:** A form of kinetic energy—commonly called "heat"—that is produced by the movement of atomic or molecular particles. The greater the motion of these particles relative to one another, the greater the thermal energy.

**TORR:** An SI unit, also known as the millimeter of mercury, that represents the pressure required to raise a column of mercury 1 mm. The torr, equal to 133 Pascals, is named for the Italian physicist Evangelista Torricelli (1608-1647), who invented the barometer.

much, much more slowly. Two seconds after impact, which is an eternity in terms of the processes involved, the pressure inside the bag has returned to 1 atm.

The chemistry of the airbag is particularly interesting. The bag releases inert, or non-reactive, nitrogen gas, which poses no hazard to human life; yet one of the chemical ingredients in

the airbag is so lethal that some environmentalist groups have begun to raise concerns over its presence in airbags. This is sodium azide ($NaN_3$), one of three compounds—along with potassium nitrate ($KNO_3$) and silicon dioxide ($SiO_2$)—present in an airbag prior to inflation.

The sodium azide and potassium nitrate react to one another, producing a burst of hot nitrogen gas in two back-to-back reactions. In the fractions of a second during which this occurs, the airbag becomes like a solid-rocket booster, experiencing a relatively slow detonation known as "deflagration."

The first reaction releases nitrogen gas, which fills the bag, while the second reaction leaves behind the by-products potassium oxide ($K_2O$) and sodium oxide ($Na_2O$). These combine with the silicon dioxide to produce a safe, stable compound known as alkaline silicate. The latter, similar to the sand used for making glass, is all that remains in the airbag after the nitrogen gas has escaped.

## WHERE TO LEARN MORE

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# ATOMS AND MOLECULES

ATOMS

ATOMIC MASS

ELECTRONS

ISOTOPES

IONS AND IONIZATION

MOLECULES

# ATOMS

## CONCEPT

Our world is made up of atoms, yet the atomic model of the universe is nonetheless considered a "theory." When scientists know beyond all reasonable doubt that a particular principle is the case, then it is dubbed a law. Laws address the fact that certain things happen, as well as how they happen. A theory, on the other hand, attempts to explain why things happen. By definition, an idea that is dubbed a theory has yet to be fully proven, and such is the case with the atomic theory of matter. After all, the atom cannot be seen, even with electron microscopes—yet its behavior can be studied in terms of its effects. Atomic theory explains a great deal about the universe, including the relationship between chemical elements, and therefore (as with Darwin's theory concerning biological evolution), it is generally accepted as fact. The particulars of this theory, including the means by which it evolved over the centuries, are as dramatic as any detective story. Nonetheless, much still remains to be explained about the atom—particularly with regard to the smallest items it contains.

## HOW IT WORKS

### Why Study Atoms?

Many accounts of the atom begin with a history of the growth in scientists' understanding of its structure, but here we will take the opposite approach, first discussing the atom in terms of what physicists and chemists today understand. Only then will we examine the many challenges scientists faced in developing the current atomic model: false starts, wrong theories, right roads not taken, incomplete models. In addition, we will explore the many insights added along the way as, piece by piece, the evidence concerning atomic behavior began to accumulate.

People who are not scientifically trained tend to associate studies of the atom with physics, not chemistry. While it is true that physicists study atomic structure, and that much of what scientists know today about atoms comes from the work of physicists, atomic studies are even more integral to chemistry than to physics. At heart, chemistry is about the interaction of different atomic and molecular structures: their properties, their reactions, and the ways in which they bond.

**WHAT THE ATOM MEANS TO CHEMISTRY.** Just as a writer in English works with the 26 letters of the alphabet, a chemist works with the 100-plus known elements, the fundamental and indivisible substances of all matter. And what differentiates the elements, ultimately, from one another is not their color or texture, or even the phase of matter—solid, gas, or liquid—in which they are normally found. Rather, the defining characteristic of an element is the atom that forms its basic structure.

The number of protons in an atom is the critical factor in differentiating between elements, while the number of neutrons alongside the protons in the nucleus serves to distinguish one isotope from another. However, as important as elements and even isotopes are to the work of a chemist, the components of the atom's nucleus have little direct bearing on the atomic activity that brings about chemical reactions and chemical bonding. All the chemical "work" of an atom is done by particles vastly smaller in mass than



John Dalton.

either the protons or neutrons—fast-moving little bundles of energy called electrons.

Moving rapidly through the space between the nucleus and the edge of the atom, electrons sometimes become dislodged, causing the atom to become a positively charged ion. Conversely, sometimes an atom takes on one or more electrons, thus acquiring a negative charge. Ions are critical to the formation of some kinds of chemical bonds, but the chemical role of the electron is not limited to ionic bonds.

In fact, what defines an atom's ability to bond with another atom, and therefore to form a molecule, is the specific configuration of its electrons. Furthermore, chemical reactions are the result of changes in the arrangement of electrons, not of any activity involving protons or neutrons. So important are electrons to the interactions studied in chemistry that a separate essay has been devoted to them.

## What an Atom Is

**basic atomic structure.** The definitions of atoms and elements seems, at first glance, almost circular: an element is a substance made up of only one kind of atom, and an atom is the smallest particle of an element that retains all the chemical and physical properties of the element. In fact, these two definitions do not form a closed loop, as they would if it were stated that an element is something made up of atoms. Every item of matter that exists, except for the subatomic particles discussed in this essay, is made up of atoms. An element, on the other hand, is—as stated in its definition—made up of only one kind of atom. "Kind of atom" in this context refers to the number of protons in its nucleus.

Protons are one of three basic subatomic particles, the other two being electrons and neutrons. As we shall see, there appear to be particles even smaller than these, but before approaching these "sub-subatomic" particles, it is necessary to address the three most significant components of an atom. These are distinguished from one another in terms of electric charge: protons are positively charged, electrons are negative in charge, and neutrons have no electrical charge. As with the north and south poles of magnets, positive and negative charges attract one another, whereas like charges repel. Atoms have no net charge, meaning that the protons and electrons cancel out one another.

**evolving models of the atom.** Scientists originally thought of an atom as a sort of closed sphere with a relatively hard shell, rather like a ball bearing. Nor did they initially understand that atoms themselves are divisible, consisting of the parts named above. Even as awareness of these three parts emerged in the last years of the nineteenth century and the first part of the twentieth, it was not at all clear how they fit together.

At one point, scientists believed that electrons floated in a cloud of positive charges. This was before the discovery of the nucleus, where the protons and neutrons reside at the heart of the atom. It then became clear that electrons were moving around the nucleus, but how? For a time, a planetary model seemed appropriate: in other words, electrons revolved around the nucleus much as planets orbit the Sun. Eventually, however—as is often the case with scientific discovery—this model became unworkable, and had to be replaced by another.

The model of electron behavior accepted today depicts the electrons as forming a cloud around the nucleus—almost exactly the opposite of what physicists believed a century ago. The use of the term "cloud" may perhaps be a bit mis-

leading, implying as it does something that simply hovers. In fact, the electron, under normal circumstances, is constantly moving. The paths of its movement around the nucleus are nothing like that of a planet's orbit, except inasmuch as both models describe a relatively small object moving around a relatively large one.

The furthest edges of the electron's movement define the outer perimeters of the atom. Rather than being a hard-shelled little nugget of matter, an atom—to restate the metaphor mentioned above—is a cloud of electrons surrounding a nucleus. Its perimeters are thus not sharply delineated, just as there is no distinct barrier between Earth's atmosphere and space itself. Just as the air gets thinner the higher one goes, so it is with an atom: the further a point is from the nucleus, the less the likelihood that an electron will pass that point on a given orbital path.

## Nucleons

**Mass number and atomic number.** The term nucleon is used generically to describe the relatively heavy particles that make up an atomic nucleus. Just as "sport" can refer to football, basketball, or baseball, or any other item in a similar class, such as soccer or tennis, "nucleon" refers to protons and neutrons. The sum of protons and neutrons is sometimes called the nucleon number, although a more commonly used term is mass number.

Though the electron is the agent of chemical reactions and bonding, it is the number of protons in the nucleus that defines an atom as to its element. Atoms of the same element always have the same number of protons, and since this figure is unique for a given element, each element is assigned an atomic number equal to the number of protons in its nucleus. The atoms are listed in order of atomic number on the periodic table of elements.

**Atomic mass and isotopes.** A proton has a mass of $1.673 \cdot 10^{-24}$ g, which is very close to the established figure for measuring atomic mass, the atomic mass unit. At one time, the basic unit of atomic mass was equal to the mass of one hydrogen atom, but hydrogen is so reactive—that is, it tends to combine readily with other atoms to form a molecule, and hence a compound—that it is difficult to isolate. Instead, the atomic mass unit is today defined as 1/12 of the mass of a carbon-12 atom. That figure is exactly $1.66053873 \cdot 10^{-24}$ grams.

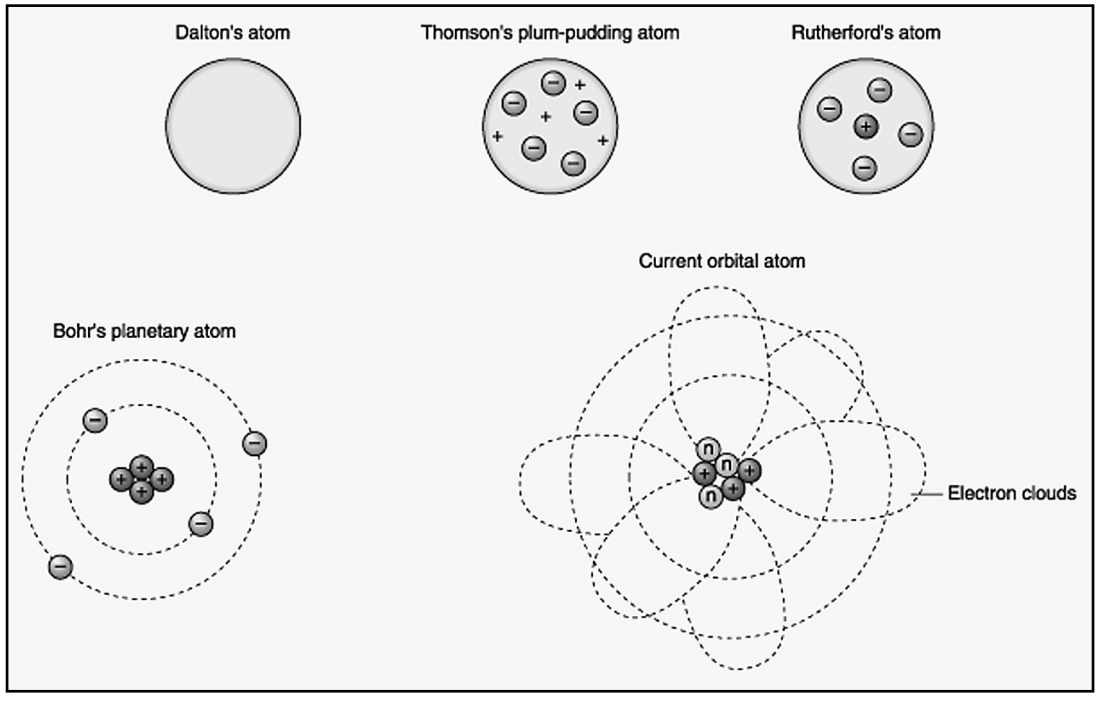


Niels Bohr.

The mention of carbon-12, a substance found in all living things, brings up the subject of isotopes. The "12" in carbon-12 refers to its mass number, or the sum of protons and neutrons. Two atoms may be of the same element, and thus have the same number of protons, yet differ in their number of neutrons—which means a difference both in mass number and atomic mass. Such differing atoms of the same element are called isotopes. Isotopes are often designated by symbols showing mass number to the upper left of the chemical symbol or element symbol—for instance, $^{12}C$ for carbon-12.

**Electric charge.** Protons have a positive electric charge of 1, designated either as 1+ or +1. Neutrons, on the other hand, have no electric charge. It appears that the 1+ charge of a proton and the 0 charge of a neutron are the products of electric charges on the part of even smaller particles called quarks. A quark may either have a positive electric charge of less than 1+, in which case it is called an "up quark"; or a negative charge of less than 1–, in which case it is called a "down quark."

Research indicates that a proton contains two up quarks, each with a charge of 2/3+, and




The evolution of atomic theory.

one down quark with a charge of 1/3–. This results in a net charge of 1+. On the other hand, a neutron is believed to hold one up quark with a charge of 2/3+, and two down quarks with charges of 1/3– each. Thus, in the neutron, the up and down quarks cancel out one another, and the net charge is zero.

A neutron has about the same mass as a proton, but other than its role in forming isotopes, the neutron's function is not exactly clear. Perhaps, it has been speculated, it binds protons—which, due to their positive charges, tend to repel one another—together at the nucleus.

## Electrons

An electron is much smaller than a proton or neutron, and has much less mass; in fact, its mass is equal to 1/1836 that of a proton, and 1/1839 that of a neutron. Yet the area occupied by electrons—the region through which they move—constitutes most of the atom's volume. If the nucleus of an atom were the size of a BB (which, in fact, is billions of times larger than a nucleus), the furthest edge of the atom would be equivalent to the highest ring of seats around an indoor sports arena. Imagine the electrons as incredibly fast-moving insects buzzing constantly through the arena, passing by the BB but then flitting to the edges or points in between, and you have something approaching an image of the atom's interior.

How fast does an electron move? Speeds vary depending on a number of factors, but it can move nearly as fast as light: 186,000 mi (299,339 km) per second. On the other hand, for an item of matter near absolute zero in temperature, the velocity of the electron is much, much less. In any case, given the fact that an electron has enough negative charge to cancel out that of the proton, it must be highly energized. After all, this would be like an electric generator weighing 1 lb having as much power as a generator that weighed 1 ton.

According to what modern scientists know or hypothesize concerning the inner structure of the atom, electrons are not made up of quarks; rather, they are part of a class of particles called leptons. It appears that leptons, along with quarks and what are called exchange particles, constitute the elementary particles of atoms—particles on a much more fundamental level than that of the proton and neutron.

Electrons are perhaps the most intriguing parts of an atom. Their mass is tiny, even in atomic terms, yet they possess enough charge to counteract a "huge" proton. They are capable, in certain situations, of moving from one atom to

another, thus creating ions, and depending on their highly complex configuration and ability to rearrange their configuration, they facilitate or prevent chemical reactions.

## REAL-LIFE APPLICATIONS

### Ancient Greek Theories of Matter

The first of the Greek philosophers, and the first individual in Western history who deserves to be called a scientist, was Thales (c. 625-c. 547 B.C.) of Miletus. (Miletus is in Greek Asia Minor, now part of Turkey.) Among his many achievements were the correct prediction of a solar eclipse, and one of the first-ever observations of electricity, when he noted the electrification of amber by friction.

But perhaps the greatest of Thales's legacies was his statement that "Everything is water." This represented the first attempt to characterize the nature of all physical reality. It set off a debate concerning the fundamental nature of matter that consumed Greek philosophers for two centuries. Later, philosophers attempted to characterize matter in terms of fire or air. In time, however, there emerged a school of thought concerned not with identifying matter as one particular thing or another, but with recognizing a structural consistency in all of matter. Among these were the philosophers Leucippus (c. 480-c. 420 B.C.) and his student Democritus (c. 460-370 B.C.)

**DEMOCRITUS'S "ATOMS".** Leucippus and Democritus proposed a new and highly advanced model for the tiniest point of physical space. Democritus, who actually articulated these ideas (far less is known about Leucippus) began with a "thought experiment," imagining what would happen if an item of matter were subdivided down to its smallest piece. This tiniest fragment, representing an item of matter that could not be cut into smaller pieces, he called by a Greek term meaning "no cut": *atomos*.

Democritus was not necessarily describing matter in a concrete, scientific way: his "atoms" were idealized philosophical constructs rather than purely physical units. Yet, he came amazingly close, and indeed much closer than any thinker for the next 22 centuries, to identifying the fundamental structure of physical reality. Why did it take so long for scientists to come back around to the atomic model? The principal culprit, who advanced an erroneous theory of matter, also happened to be one of the greatest thinkers of all time: Aristotle (384-322 B.C..)

**ARISTOTLE'S "ELEMENTS".** Aristotle made numerous contributions to science, including his studies in botany and zoology, as well as his explanation of the four causes, a significant attempt to explain events by means other than myth or superstition. In the area of the physical sciences, however, Aristotle's impact was less than beneficial. Most notably, in explaining why objects fall when dropped, he claimed that the ground was their "natural" destination—a fallacy later overturned with the gravitational model developed by Galileo Galilei (1564-1642) and Sir Isaac Newton (1642-1727).

The ideas Aristotle put forward concerning what he called "natural motion" were a product of his equally faulty theories with regard to what today's scientists refer to as chemistry. In ancient times, chemistry, as such, did not exist. Long before Aristotle's time, Egyptian embalmers and metallurgists used chemical processes, but they did so in a practical, applied manner, exerting little effort toward what could be described as scientific theory. Philosophers such as Aristotle, who were some of the first scientists, made little distinction between physical and chemical processes. Thus, whereas physics is understood today as an important background for chemistry, Aristotle's "physics" was actually an outgrowth of his "chemistry."

Rejecting Democritus's atomic model, Aristotle put forward his own view of matter. Like Democritus, he believed that matter was composed of very small components, but these he identified not as atoms, but as "elements": earth, air, fire, and water. He maintained that all objects consisted, in varying degrees, of one or more of these, and based his explanation of gravity on the relative weights of each element. Water sits on top of the earth, he explained, because it is lighter, yet air floats above the water because it is lighter still—and fire, lightest of all, rises highest. Furthermore, he claimed that the planets beyond Earth were made up of a "fifth element," or quintessence, of which little could be known.

In fairness to Aristotle, it should be pointed out that it was not his fault that science all but

died out in the Western world during the period from about A.D. 200 to about 1200. Furthermore, he did offer an accurate definition of an element, in a general sense, as "one of those simple bodies into which other bodies can be decomposed, and which itself is not capable of being divided into others." As we shall see, the definition used today is not very different from Aristotle's. However, to define an element scientifically, as modern chemists do, it is necessary to refer to something Aristotle rejected: the atom. So great was his opposition to Democritus's atomic theory, and so enormous was Aristotle's influence on learning for more than 1,500 years following his death, that scientists only began to reconsider atomic theory in the late eighteenth century.

## A Maturing Concept of Elements

**Boyle's idea of elements.** One of the first steps toward an understanding of the chemical elements came with the work of English physicist and chemist Robert Boyle (1627-1691). Building on the usable definition of an element provided by Aristotle, Boyle maintained no substance was an element if it could be broken down into other substances. Thus, air could be eliminated from the list of "elements," because, clearly, it could be separated into more than one elemental substance. (In fact, none of the four "elements" identified by Aristotle even remotely qualifies as an element in modern chemistry.)

Boyle, nonetheless, still clung to aspects of alchemy, a pseudo-science based on the transformation of "base metals," for example, the metamorphosis of iron into gold. Though true chemistry grew out of alchemy, the fundamental proposition of alchemy was faulty: if one metal can be turned into another, then that means that metals are not elements, which, in fact, they are. Nonetheless, Boyle's studies led to the identification of numerous elements—that is, items that really are elements—in the years that followed.

**Lavoisier and Proust: constant composition.** A few years after Boyle came two French chemists who extended scientific understanding of the elements. Antoine Lavoisier (1743-1794) affirmed the definition of an element as a simple substance that could not be broken down into a simpler substance, and noted that elements always react with one another in the same proportions.

Joseph-Louis Proust (1754-1826) put forward the law of constant composition, which holds that a given compound always contains the same proportions of mass between elements. Another chemist of the era had claimed that the composition of a compound varies in accordance with the reactants used to produce it. Proust's law of constant composition made it clear that any particular compound will always have the same composition.

## Early Modern Understanding of the Atom

**Dalton and Avogadro: atoms and molecules.** The work of Lavoisier and Proust influenced a critical figure in the development of the atomic model: English chemist John Dalton (1766-1844). In *A New System of Chemical Philosophy* (1808), Dalton put forward the idea that nature is composed of tiny particles, and in so doing he adopted Democritus's word "atom" to describe these basic units. This idea, which Dalton had formulated five years earlier, marked the starting-point of modern atomic theory.

Dalton recognized that the structure of atoms in a particular element or compound is uniform, but maintained that compounds are made up of compound atoms: in other words, water, for instance, is a compound of "water atoms." However, water is not an element, and thus, it was necessary to think of its atomic composition in a different way—in terms of molecules rather than atoms. Dalton's contemporary Amedeo Avogadro (1776-1856), an Italian physicist, became the first scientist to clarify the distinction between atoms and molecules.

The later development of the mole, which provided a means whereby equal numbers of molecules could be compared, paid tribute to Avogadro by designating the number of molecules in a mole as "Avogadro's number." Another contemporary, Swedish chemist Jons Berzelius (1779-1848), maintained that equal volumes of gases at the same temperature and pressure contained equal numbers of atoms. Using this idea, he compared the mass of various reacting gases, and developed a system of comparing the mass of various atoms in relation to the lightest one, hydrogen. Berzelius also introduced the system

of chemical symbols—H for hydrogen, O for oxygen, and so on—in use today.

**Brownian motion and kinetic theory.** Yet another figure whose dates overlapped with those of Dalton, Avogadro, and Berzelius was Scottish botanist Robert Brown (1773-1858). In 1827, Brown noted a phenomenon that later had an enormous impact on the understanding of the atom. While studying pollen grains under a microscope, Brown noticed that the grains underwent a curious zigzagging motion in the water. The pollen assumed the shape of a colloid, a pattern that occurs when particles of one substance are dispersed—but not dissolved—in another substance. At first, Brown assumed that the motion had a biological explanation—that is, it resulted from life processes within the pollen—but later, he discovered that even pollen from long-dead plants behaved in the same way.

Brown never understood what he was witnessing. Nor did a number of other scientists, who began noticing other examples of what came to be known as Brownian motion: the constant but irregular zigzagging of colloidal particles, which can be seen clearly through a microscope. Later, however, Scottish physicist James Clerk Maxwell (1831-1879) and others were able to explain this phenomenon by what came to be known as the kinetic theory of matter.

Kinetic theory is based on the idea that molecules are constantly in motion: hence, the water molecules were moving the pollen grains Brown observed. Pollen grains are many thousands of times as large as water molecules, but since there are so many molecules in even a drop of water, and their motion is so constant but apparently random, they are bound to move a pollen grain once every few thousand collisions.

## Mendeleev and the Periodic Table

In 1869, Russian chemist Dmitri Mendeleev (1834-1907) introduced a highly useful system for organizing the elements, the periodic table. Mendeleev's table is far more than just a handy chart listing elements: at once simple and highly complex, it shows elements in order of increasing atomic mass, and groups together those exhibiting similar forms of chemical behavior and structure.

Reading from right to left and top to bottom, the periodic table, as it is configured today, lists atoms in order of atomic number, generally reflected by a corresponding increase in average atomic mass. As Mendeleev observed, every eighth element on the chart exhibits similar characteristics, and thus the chart is organized in columns representing specific groups of elements.

The patterns Mendeleev observed were so regular that for any "hole" in his table, he predicted that an element would be discovered that would fill that space. For instance, at one point there was a gap between atomic numbers 71 and 73 (lutetium and tantalum, respectively). Mendeleev indicated that an atom would be found for the space, and 15 years after this prediction, the element germanium was isolated.

However, much of what defines an element's place on the chart today relates to subatomic particles—protons, which determine atomic number, and electrons, whose configurations explain certain chemical similarities. Mendeleev was unaware of these particles: from the time he created his table, it was another three decades before the discovery of the first of these particles, the electron. Instead, he listed the elements in an order reflecting outward characteristics now understood to be the result of the quantity and distribution of protons and electrons.

## Electromagnetism and Radiation

The contribution of Mendeleev's contemporary, Maxwell, to the understanding of the atom was not limited to his kinetic theory. Building on the work of British physicist and chemist Michael Faraday (1791-1867) and others, in 1865 he published a paper outlining a theory of a fundamental interaction between electricity and magnetism. The electromagnetic interaction, as it later turned out, explained something that gravitation, the only other form of fundamental interaction known at the time, could not: the force that held together particles in an atom.

The idea of subatomic particles was still a long time in coming, but the model of electromagnetism helped make it possible. In the long run, electromagnetism was understood to encompass a whole spectrum of energy radiation, including radio waves; infrared, visible, and ultraviolet light; x rays; and gamma rays. But this,

too, was the product of work on the part of numerous individuals, among whom was English physicist William Crookes (1832-1919).

In the 1870s, Crookes developed an apparatus later termed a Crookes tube, with which he sought to analyze the "rays"—that is, radiation—emitted by metals. The tube consisted of a glass bulb, from which most of the air had been removed, encased between two metal plates or electrodes, referred to as a cathode and an anode. A wire led outside the bulb to an electric source, and when electricity was applied to the electrodes, the cathodes emitted rays. Crookes concluded that the cathode rays were particles with a negative electric charge that came from the metal in the cathode plate.

**RADIATION.** In 1895, German physicist Wilhelm Röntgen (1845-1923) noticed that photographic plates held near a Crookes tube became fogged, and dubbed the rays that had caused the fogging "x rays." A year after Röntgen's discovery, French physicist Henri Becquerel (1852-1908) left some photographic plates in a drawer with a sample of uranium. Uranium had been discovered more than a century before; however, there were few uses for it until Becquerel discovered that the uranium likewise caused a fogging of the photographic plates.

Thus radioactivity, a type of radiation brought about by atoms that experience radioactive decay was discovered. The term was coined by Polish-French physicist and chemist Marie Curie (1867-1934), who with her husband Pierre (1859-1906), a French physicist, was responsible for the discovery of several radioactive elements.

## The Rise and Fall of the Plum Pudding Model

Working with a Crookes tube, English physicist J. J. Thomson (1856-1940) hypothesized that the negatively charged particles Crookes had observed were being emitted by atoms, and in 1897, he gave a name to these particles: electrons. The discovery of the electron raised a new question: if Thomson's particles exerted a negative charge, from whence did the counterbalancing positive charge come?

An answer, of sorts, came from William Thomson, not related to the other Thomson and, in any case, better known by his title as Lord Kelvin (1824-1907). Kelvin compared the structure of an atom to an English plum pudding: the electrons were like raisins, floating in a positively charged "pudding"—that is, an undifferentiated cloud of positive charges.

Kelvin's temperature scale contributed greatly to the understanding of molecular motion as encompassed in the kinetic theory of matter. However, his model for the distribution of charges in an atom—charming as it may have been—was incorrect. Nonetheless, for several decades, the "plum pudding model," as it came to be known, remained the most widely accepted depiction of the way that electric charges were distributed in an atom. The overturning of the plum pudding model was the work of English physicist Ernest Rutherford (1871-1937), a student of J. J. Thomson.

**RUTHERFORD IDENTIFIES THE NUCLEUS.** Rutherford did not set out to disprove the plum pudding model; rather, he was conducting tests to find materials that would block radiation from reaching a photographic plate. The two materials he identified, which were, respectively, positive and negative in electric charge, he dubbed alpha and beta particles. (An alpha particle is a helium nucleus stripped of its electrons, such that it has a positive charge of 2; beta particles are either electrons or positively charged subatomic particles called positrons. The beta particle Rutherford studied was an electron emitted during radioactive decay.)

Using a piece of thin gold foil with photographic plates encircling it, Rutherford bombarded the foil with alpha particles. Most of the alpha particles went straight through the foil—as they should, according to the plum pudding model. However, a few particles were deflected from their course, and some even bounced back. Rutherford later said it was as though he had fired a gun at a piece of tissue paper, only to see the tissue deflect the bullets. Analyzing these results, Rutherford concluded that there was no "pudding" of positive charges: instead, the atom had a positively charged nucleus at its center.

## The Nucleus Emerges

**PROTONS AND ISOTOPES.** In addition to defining the nucleus, Rutherford also gave a name to the particles that imparted its positive charge: protons. But just as the identification of the electron had raised new questions that, in being answered, led to the discovery of the proton, Rutherford's achievement only

brought up new anomalies concerning the behavior of the nucleus.

Together with English chemist Frederick Soddy (1877-1956), Rutherford discovered that when an atom emitted alpha or beta particles, its atomic mass changed. Soddy had a name for atoms that displayed this type of behavior: isotopes. Certain types of isotopes, Soddy and Rutherford went on to conclude, had a tendency to decay, moving toward stabilization, and this decay explained radioactivity.

**CLARIFYING THE PERIODIC TABLE.** Soddy concluded that atomic mass, as measured by Berzelius, was actually an average of the mass figures for all isotopes within that element. This explained a problem with Mendeleev's periodic table, in which there seemed to be irregularities in the increase of atomic mass from element to element. The answer to these variations in mass, it turned out, related to the number of isotopes associated with a given element: the greater the number of isotopes, the more these affected the overall measure of the element's mass.

By this point, physicists and chemists had come to understand that various levels of energy in matter emitted specific electromagnetic wavelengths. Welsh physicist Henry Moseley (1887-1915) experimented with x rays, bombarding atoms of different elements with high levels of energy and observing the light they gave off as they cooled. In the course of these tests, he uncovered an astounding mathematical relationship: the amount of energy a given element emitted was related to its atomic number.

Furthermore, the atomic number corresponded to the number of positive charges—this was in 1913, before Rutherford had named the proton—in the nucleus. Mendeleev had been able to predict the discovery of new elements, but such predictions had remained problematic. When scientists understood the idea of atomic number, however, it became possible to predict the existence of undiscovered elements with much greater accuracy.

**NEUTRONS.** Yet again, discoveries—the nucleus, protons, and the relationship between these and atomic number—only created new questions. (This, indeed, is one of the hallmarks of an active scientific theory. Rather than settling questions, science is about raising new ones, and thus improving the quality of the questions that are asked.) Once Rutherford had identified the proton, and Moseley had established the number of protons, the mystery at the heart of the atom only grew deeper.

Scientists had found that the measured mass of atoms could not be accounted for by the number of protons they contained. Certainly, the electrons had little to do with atomic mass: by then it had been shown that the electron weighed about 0.06% as much as a proton. Yet for all elements other than protium (the first of three hydrogen isotopes), there was a discrepancy between atomic mass and atomic number. Clearly, there had to be something else inside the nucleus.

In 1932, English physicist James Chadwick (1891-1974) identified that "something else." Working with radioactive material, he found that a certain type of subatomic particle could penetrate lead. All other known types of radiation were stopped by the lead, and therefore, Chadwick reasoned that this particle must be neutral in charge. In 1932, he won the Nobel Prize in Physics for his discovery of the neutron.

## The Nuclear Explosion

**ISOTOPES AND RADIOACTIVITY.** Chadwick's discovery clarified another mystery, that of the isotope, which had been raised by Rutherford and Soddy several decades earlier. Obviously, the number of protons in a nucleus did not change, but until the identification of the neutron, it had not been clear what it was that did change. At that point, it was understood that two atoms may have the same atomic number—and hence be of the same element—yet they may differ in number of neutrons, and thus be isotopes.

As the image of what an isotope was became clearer, so too did scientists' comprehension of radioactivity. Radioactivity, it was discovered, was most intense where an isotope was the most unstable—that is, in cases where an isotope had the greatest tendency to experience decay. Uranium had a number of radioactive isotopes, such as $^{235}U$, and these found application in the burgeoning realm of nuclear power—both the destructive power of atomic bombs, and later the constructive power of nuclear energy plants.

**FISSION VS. FUSION.** In nuclear fission, or the splitting of atoms, uranium isotopes (or other radioactive isotopes) are bom-

barded with neutrons, splitting the uranium nucleus in half and releasing huge amounts of energy. As the nucleus is halved, it emits several extra neutrons, which spin off and split more uranium nuclei, creating still more energy and setting off a chain reaction. This explains the destructive power in an atomic bomb, as well as the constructive power—providing energy to homes and businesses—in a nuclear power plant. Whereas the chain reaction in an atomic bomb becomes an uncontrolled explosion, in a nuclear plant the reaction is slowed and controlled.

Yet nuclear fission is not the most powerful form of atomic reaction. As soon as scientists realized that it was possible to force particles out of a nucleus, they began to wonder if particles could be forced into the nucleus. This type of reaction, known as fusion, puts even nuclear fission, with its awesome capabilities, to shame: nuclear fusion is, after all, the power of the Sun. On the surface of that great star, hydrogen atoms reach incredible temperatures, and their nuclei fuse to create helium. In other words, one element actually transforms into another, releasing enormous amounts of energy in the process.

**NUCLEAR ENERGY IN WAR AND PEACE.** The atomic bombs dropped by the United States on Japan in 1945 were fission bombs. These were the creation of a group of scientists—legendary figures such as American physicist J. Robert Oppenheimer (1904-1967), American mathematician John von Neumann (1903-1957), American physicist Edward Teller (1908-), and Italian physicist Enrico Fermi (1901-1954)—involved in the Manhattan Project at Las Alamos, New Mexico.

Some of these geniuses, particularly Oppenheimer, were ambivalent about the moral implications of the enormous destructive power they created. However, most military historians believe that far more lives—both Japanese and American—would have been lost if America had been forced to conduct a land invasion of Japan. As it was, the Japanese surrendered shortly after the cities of Hiroshima and Nagasaki suffered the devastating effects of fission-based explosions.

By 1952, U.S. scientists had developed a "hydrogen," or fusion bomb, thus raising the stakes greatly. This was a bomb that possessed far more destructive capability than the ones dropped over Japan. Fortunately, the Hiroshima and Nagasaki bombs were the only ones dropped in wartime, and a ban on atmospheric nuclear testing has greatly reduced the chances of human exposure to nuclear fallout of any kind. With the end of the arms race between the United States and the Soviet Union, the threat of nuclear destruction has receded somewhat—though it will perhaps always be a part of human life.

Nonetheless, fear of nuclear power, spawned as a result of the arms race, continues to cloud the future of nuclear plants that generate electricity—even though these, in fact, emit less radioactive pollution than coal- or gas-burning power plants. At the same time, scientists continue to work on developing a process of power generation by means of nuclear fusion, which, if and when it is achieved, will be one of the great miracles of science.

**PARTICLE ACCELERATORS.** One of the tools used by scientists researching nuclear fusion is the particle accelerator, which moves streams of charged particles—protons, for instance—faster and faster. These fast particles are then aimed at a thin plate composed of a light element, such as lithium. If the proton manages to be "captured" in the nucleus of a lithium atom, the resulting nucleus is unstable, and breaks into alpha particles.

This method of induced radioactivity is among the most oft- used means of studying nuclear structure and subatomic particles. In 1932, the same year that Chadwick discovered the neutron, English physicist John D. Cockcroft (1897-1967) and Irish physicist Ernest Walton (1903-1995) built the first particle accelerator. Some particle accelerators today race the particles in long straight lines or, to save space, in ringed paths several miles in diameter.

## Quantum Theory and Beyond

**THE CONTRIBUTION OF RELATIVITY.** It may seem strange that in this lengthy (though, in fact, quite abbreviated!) overview of developments in understanding of the atom, no mention has been made of the figure most associated with the atom in the popular mind: German-American physicist Albert Einstein (1879-1955). The reasons for this are several. Einstein's relativity theory addresses physical, rather than chemical, processes, and did not directly contribute to enhanced understanding of atomic structure or elements. The heart of relativity the-

ory is the famous formula $E = mc^2$, which means that every item of matter possesses energy proportional to its mass multiplied by the squared speed of light.

The value of $mc^2$, of course, is an enormous amount of energy, and in order to be released in significant quantities, an article of matter must experience the kinetic energy associated with very, very high speeds—speeds close to that of light. Obviously, the easiest thing to accelerate to such a speed is an atom, and hence, nuclear energy is a result of Einstein's famous equation. Nonetheless, it should be stressed that although Einstein is associated with unlocking the power of the atom, he did little to explain what atoms are.

However, in the course of developing his relativity theory in 1905, Einstein put to rest a question about atoms and molecules that still remained unsettled after more than a century. Einstein's analysis of Brownian motion, combined with the confirmation of his results by French physicist Jean Baptiste Perrin (1870-1942), showed conclusively that yes, atoms and molecules do exist. It may seem amazing that as recently as 1905, this was still in doubt; however, this only serves to illustrate the arduous path scientists must tread in developing a theory that accurately explains the world.

**PLANCK'S QUANTUM THEORY.** A figure whose name deserves to be as much a household word as Einstein's—though it is not—is German physicist Max Planck (1858-1947). It was Planck who initiated the quantum theory that Einstein developed further, a theory that prevails today in the physical sciences.

At the atomic level, Planck showed, energy is emitted in tiny packets or "quanta." Each of these energy packets is indivisible, and the behavior of quanta redefine the old rules of physics handed down from Newton and Maxwell. Thus, it is Planck's quantum theory, rather than Einstein's relativity, that truly marks the watershed, or "before and after," between classical physics and modern physics.

Quantum theory is important not only to physics, but to chemistry as well. It helps to explain the energy levels of electrons, which are not continuous, as in a spectrum, but jump between certain discrete points. The quantum model is now also applied to the overall behavior of the electron; but before this could be fully achieved, scientists had to develop a new understanding of the way electrons move around the nucleus.

**BOHR'S PLANETARY MODEL OF THE ATOM.** As was often the case in the history of the atom, a man otherwise respected as a great scientist put forward a theory of atomic structure that at first seemed convincing, but ultimately turned out to be inaccurate. In this case, it was Danish physicist Niels Bohr (1885-1962), a seminal figure in the development of nuclear fission.

Using the observation, derived from quantum theory, that electrons only occupied specific energy levels, Bohr hypothesized that electrons orbited around a nucleus in the same way that planets orbit the Sun. There is no reason to believe that Bohr formed this hypothesis for any sentimental reasons—though, of course, scientists are just as capable of prejudice as anyone. His work was based on his studies; nonetheless, it is easy to see how this model seemed appealing, showing as it did an order at the subatomic level reflecting an order in the heavens.

**ELECTRON CLOUDS.** Many people today who are not scientifically trained continue to think that an atom is structured much like the Solar System. This image is reinforced by symbolism, inherited from the 1950s, that represents "nuclear power" by showing a dot (the nucleus) surrounded by ovals at angles to one another, representing the orbital paths of electrons. However, by the 1950s, this model of the atom had already been overturned.

In 1923, French physicist Louis de Broglie (1892-1987) introduced the particle-wave hypothesis, which indicated that electrons could sometimes have the properties of waves—an eventuality not encompassed in the Bohr model. It became clear that though Bohr was correct in maintaining that electrons occupy specific energy levels, his planetary model was inadequate for explaining the behavior of electrons.

Two years later, in 1925, German physicist Werner Heisenberg (1901-1976) introduced what came to be known as the Heisenberg Uncertainty Principle, showing that the precise position and speed of an electron cannot be known at the same time. Austrian physicist Erwin Schrödinger (1887-1961) developed an

## KEY TERMS

**ATOM:** The smallest particle of an element that retains all the chemical and physical properties of the element. An atom can exist either alone or in combination with other atoms in a molecule. Atoms are made up of protons, neutrons, and electrons.

**ATOMIC MASS UNIT:** An SI unit (abbreviated amu), equal to $1.66 \cdot 10^{-24}$ 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 of elements 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.

**CHEMICAL SYMBOL:** A one- or two-letter abbreviation for the name of an element.

**COMPOUND:** A substance made up of atoms of more than one element. These atoms are usually joined in molecules.

**ELECTRON:** Negatively charged particles in an atom. Electrons, which spin around the protons and neutrons that make up the atom's nucleus, constitute a very small portion of the atom's mass. The number of electrons and protons is the same, thus canceling out one another; on the other hand, if an atom loses or gains electrons, it becomes an ion.

**ELEMENT SYMBOL:** Another term for chemical symbol.

**ION:** An atom or atoms 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.

**MASS NUMBER:** The sum of protons and neutrons in an atom's nucleus.

**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.

equation for calculating how an electron with a certain energy moves, identifying regions in an atom where an electron possessing a certain energy level is likely to be. Schrödinger's equation cannot, however, identify the location exactly.

Rather than being called orbits, which suggest the orderly pattern of Bohr's model, Schrödinger's regions of probability are called orbitals. Moving within these orbitals, electrons describe the shape of a cloud, as discussed much earlier in this essay; as a result, the "electron cloud" theory prevails today. This theory incorporates aspects of Bohr's model, inasmuch as electrons move from one orbital to another by absorbing or emitting a quantum of energy.

### WHERE TO LEARN MORE

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## KEY TERMS CONTINUED

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

**NUCLEON:** A generic term for the heavy particles—protons and neutrons—that make up the nucleus of an atom.

**NUCLEON NUMBER:** Another term for mass number.

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

**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 (in atomic mass units) for that particular element. Vertical columns within the periodic table indicate groups or "families" of elements with similar chemical characteristics.

**PROTON:** A positively charged particle in an atom. Protons and neutrons, which together form the nucleus around which electrons spin, have approximately the same mass—a mass that is many times greater than that of an electron.

**QUARK:** A particle believed to be a component of protons and neutrons. A quark may either have a positive electric charge of less than 1+, in which case it is called an "up quark"; or a negative charge of less than 1-, in which case it is called a "down quark."

**RADIATION:** In a general sense, radiation can refer to anything that travels in a stream, whether that stream be composed of subatomic particles or electromagnetic waves. In a more specific sense, the term relates to the radiation from radioactive materials, which can be harmful to human beings.

**RADIOACTIVITY:** A term describing a phenomenon whereby certain isotopes are subject to a form of decay brought about by the emission of high-energy particles or radiation, such as alpha particles, beta particles, or gamma rays.


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# ATOMIC MASS

## CONCEPT

Every known item of matter in the universe has some amount of mass, even if it is very small. But what about something so insignificant in mass that comparing it to a gram is like comparing a millimeter to the distance between Earth and the nearest galaxy? Obviously, special units are needed for such measurements; then again, one might ask why it is necessary to weigh atoms at all. One answer is that everything is made of atoms. More specifically, the work of a chemist requires the use of accurate atomic proportions in forming the molecules that make up a compound. The measurement of atomic mass was thus a historic challenge that had to be overcome, and the story of the ways that scientists met this challenge is an intriguing one.

## HOW IT WORKS

### Why Mass and Not Weight?

Some textbooks and other sources use the term atomic weight instead of atomic mass. The first of these is not as accurate as the second, which explains why atomic mass was chosen as the subject of this essay. Indeed, the use of "atomic weight" today merely reflects the fact that scientists in the past used that expression and spoke of "weighing" atoms. Though "weigh" is used as a verb in this essay, this is only because it is less cumbersome than "measure the mass of." (In addition, "atomic weight" may be mentioned when discussing studies by scientists of the nineteenth century, who applied that term rather than atomic mass.)

One might ask why such pains have been taken to make the distinction. Mass is, after all, basically the same as weight, is it not? In fact it is not, though people are accustomed to thinking in those terms since most weight scales provide measurements in both pounds and kilograms. However, the pound is a unit of weight in the English system, whereas a kilogram is a unit of mass in the metric and SI systems. Though the two are relatively convertible on Earth, they are actually quite different. (Of course it would make no more sense to measure atoms in pounds or kilograms than to measure the width of a hair in light-years; but pounds and kilograms are the most familiar units of weight and mass respectively.)

Weight is a measure of force affected by Earth's gravitational pull. Therefore a person's weight varies according to gravity, and would be different if measured on the Moon, whereas mass is the same throughout the universe. Its invariability makes mass preferable to weight as a parameter of scientific measure.

### Putting an Atom's Size and Mass in Context

Mass does not necessarily relate to size, though there is enough of a loose correlation that more often than not, we can say that an item of very small size will have very small mass. And atoms are very, very small—so much so that, until the early twentieth century, chemists and physicists had no accurate means of isolating them to determine their mass.

The diameter of an atom is about $10^{-8}$ cm. This is equal to about 0.000000003937 in—or to put it another way, an inch is about as long as 250

million atoms lined up side by side. Obviously, special units are required for describing the size of atoms. Usually, measurements are provided in terms of the angstrom, equal to $10^{-10}$ m. (In other words, there are 10 million angstroms in a millimeter.)

Measuring the spatial dimensions of an atom, however, is not nearly as important for chemists' laboratory work as measuring its mass. The mass of an atom is almost inconceivably small. It takes about $5.0 \cdot 10^{23}$ carbon atoms to equal just one gram in mass. At first, $10^{23}$ does not seem like such a huge number, until one considers that $10^6$ is already a million, meaning that $10^{23}$ is a million times a million times a million times 100,000. If $5.0 \cdot 10^{23}$ angstrom lengths—angstroms, not meters or even millimeters—were laid end to end, they would stretch from Earth to the Sun and back 107,765 times!

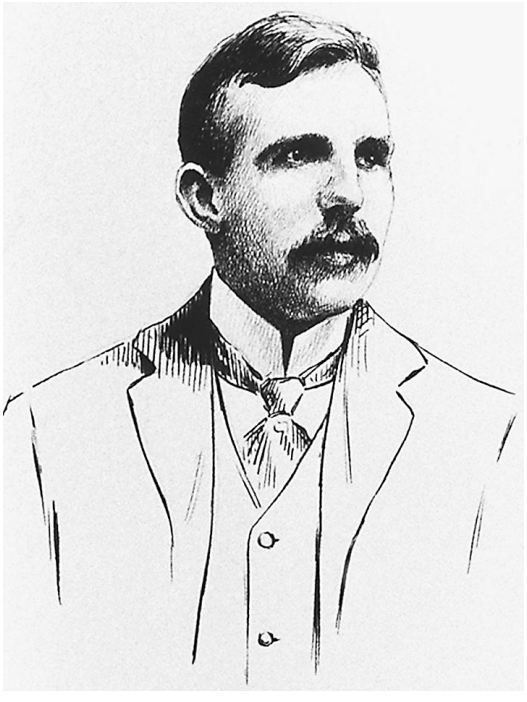
## Atomic Mass Units

It is obvious, then, that an entirely different unit is needed for measuring the mass of an atom, and for this purpose, chemists and other scientists use an atom mass unit (abbreviated amu), which is equal to $1.66 \cdot 10^{-24}$ g.

Though the abbreviation amu is used in this book, atomic mass units are sometimes designated simply by a u. On the other hand, they may be presented as numbers without any unit of measure—as for instance on the periodic table of elements.

Within the context of biochemistry and microbiology, often the term dalton (abbreviated Da or D) is used. This is useful for describing the mass of large organic molecules, typically rendered in kilodaltons (kDa). The Latin prefix kilo- indicates 1,000 of something, and "kilodalton" is much less of a tongue-twister than "kilo-amu". The term "dalton" honors English chemist John Dalton (1766-1844), who, as we shall see, introduced the concept of the atom to science.

**AVERAGE ATOMIC MASS.** Since 1960, when its value was standardized, the atomic mass unit has been officially known as the "unified atomic mass unit." The addition of the word "unified" reflects the fact that atoms are not weighed individually—a labor that would be problematic at the very least. In any case, to do so would be to reinvent the wheel, as it were, because average atomic mass figures have been established for each element.



Ernest Rutherford.

Average atomic mass figures range from 1.008 amu for hydrogen, the first element listed on the periodic table of elements, to over 250 amu for elements of very high atomic number. Figures for average atomic mass can be used to determine the average mass of a molecule as well, since a molecule is just a group of atoms joined in a structure. The mass of a molecule can be determined simply by adding together average atomic mass figures for each atom the molecule contains. A water molecule, for instance, consists of two hydrogen atoms and one oxygen atom; therefore, its mass is equal to the average atomic mass of hydrogen multiplied by two, and added to the average atomic mass of oxygen.

## Avogadro's Number and the Mole

Atomic mass units and average atomic mass are not the only components necessary for obtaining accurate mass figures where atoms are concerned. Obviously, as suggested several times already, it would be fruitless to determine the mass of individual atoms or molecules. Nor would it do to measure the mass of a few hundred, or even a few million, of these particles.



Frederick Soddy.

After all, as we have seen, it takes about 500,000 trillion million carbon atoms to equal just one gram—and a gram, after all, is still rather small in mass compared to most objects encountered in daily life. (There are 1,000 g in a kilogram, and a pound is equal to about 454 g.)

In addition, scientists need some means for comparing atoms or molecules of different substances in such a way that they know they are analyzing equal numbers of particles. This cannot be done in terms of mass, because the number of atoms in each sample varies: a gram of hydrogen, for instance, contains about 12 times as many atoms as a gram of carbon, which has an average atomic mass of 12.01 amu. What is needed, instead, is a way to designate a certain number of atoms or molecules, such that accurate comparisons are possible.

In order to do this, chemists make use of a figure known as Avogadro's number. Named after Italian physicist Amedeo Avogadro (1776-1856), it is equal to $6.022137 \times 10^{23}$. Avogadro's number, which is 6,022,137 followed by 17 zeroes, designates the quantity of molecules in a mole (abbreviated mol). The mole, a fundamental SI unit for "amount of substance," is defined precisely as the number of carbon atoms in 12.01 g of carbon. It is here that the value of Avogadro's number becomes clear: as noted, carbon has an average atomic mass of 12.01 amu, and multiplication of the average atomic mass by Avogadro's number yields a figure in grams equal to the value of the average atomic mass in atomic mass units.

## REAL-LIFE APPLICATIONS

### Early Ideas of Atomic Mass

Dalton was not the first to put forth the idea of the atom: that concept, originated by the ancient Greeks, had been around for more than 2,000 years. However, atomic theory had never taken hold in the world of science—or, at least, what passed for science prior to the seventeenth century revolution in thinking brought about by Galileo Galilei (1564-1642) and others.

Influenced by several distinguished predecessors, Dalton in 1803 formulated the theory that nature is formed of tiny particles, an idea he presented in *A New System of Chemical Philosophy* (1808). Dalton was the first to treat atoms as fully physical constructs; by contrast, ancient proponents of atomism conceived these fundamental particles in ideal or spiritual terms. Dalton described atoms as hard, solid, indivisible particles with no inner spaces—a definition that did not endure, as later scientific inquiry revealed the complexities of the atom. Yet he was correct in identifying atoms as having weight—or, as scientists say today, mass.

**THE FIRST TABLE OF ATOMIC WEIGHTS.** The question was, how could anyone determine the weight of something as small as an atom? A year after the publication of Dalton's book, a discovery by French chemist and physicist Joseph Gay-Lussac (1778-1850) and German naturalist Alexander von Humboldt (1769-1859) offered a clue. Humboldt and Gay-Lussac—famous for his gas law associating pressure and temperature—found that gases combine to form compounds in simple proportions by volume.

For instance, as Humboldt and Gay-Lussac discovered, water is composed of only two elements: hydrogen and oxygen, and these two combine in a whole-number ratio of 8:1. By separating water into its components, they found that for every part of oxygen, there were eight parts of hydrogen. Today we know that water molecules

are formed by two hydrogen atoms, with an average atomic mass of 1.008 amu each, and one oxygen atom. The ratio between the average atomic mass of oxygen (16.00 amu) and that of the two hydrogen atoms is indeed very nearly 8:1.

In the early nineteenth century, however, chemists had no concept of molecular structure, or any knowledge of the atomic masses of elements. They could only go on guesswork: hence Dalton, in preparing the world's first "Table of Atomic Weights," had to make some assumptions based on Humboldt's and Gay-Lussac's findings. Presumably, Dalton reasoned, only one atom of hydrogen combines with one atom of oxygen to form a "water atom." He assigned to hydrogen a weight of 1, and according to this, calculated the weight of oxygen as 8.

**Avogadro and Berzelius improve on Dalton's work.** The implications of Gay-Lussac's discovery that substances combined in whole-number ratios were astounding. (Gay-Lussac, who studied gases for much of his career, is usually given more credit than Humboldt, an explorer and botanist who had his hand in many things.) On the one hand, the more scientists learned about nature, the more complex it seemed; yet here was something amazingly simple. Instead of combining in proportions of, say, 8.3907 to 1.4723, oxygen and hydrogen molecules formed a nice, clean, ratio of 8 to 1. This served to illustrate the fact that, as Dalton had stated, the fundamental particles of matter must be incredibly tiny; otherwise, it would be impossible for every possible quantity of hydrogen and oxygen in water to have the same ratio.

Intrigued by the work of Gay-Lussac, Avogadro in 1811 proposed that equal volumes of gases have the same number of particles if measured at the same temperature and pressure. He also went on to address a problem raised by Dalton's work. If atoms were indivisible, as Dalton had indicated, how could oxygen exist both as its own atom and also as part of a water "atom"? Water, as Avogadro correctly hypothesized, is not composed of atoms but of molecules, which are themselves formed by the joining of two hydrogen atoms with one oxygen atom.

Avogadro's molecular theory opened the way to the clarification of atomic mass and the development of the mole, which, as we have seen, makes it possible to determine mass for large quantities of molecules. However, his ideas did not immediately gain acceptance. Only in 1860, four years after Avogadro's death, did Italian chemist Stanislao Cannizzaro (1826-1910) resurrect the concept of the molecule as a way of addressing disagreements among scientists regarding the determination of atomic mass.

In the meantime, Swedish chemist Jons Berzelius (1779-1848) had adopted Dalton's method of comparing all "atomic weights" to that of hydrogen. In 1828, Berzelius published a table of atomic weights, listing 54 elements along with their weight relative to that of hydrogen. Thus carbon, in Berzelius's system, had a weight of 12. Unlike Dalton's figures, Berzelius's are very close to those used by scientists today. By the time Russian chemist Dmitri Ivanovitch Mendeleev (1834-1907) created his periodic table in 1869, there were 63 known elements. That first table retained the system of measuring atomic mass in comparison to hydrogen.

## The Discovery of Subatomic Structures

Until scientists began to discover the existence of subatomic structures, measurements of atomic mass could not really progress. Then in 1897, English physicist J. J. Thomson (1856-1940) identified the electron. A particle possessing negative charge, the electron contributes little to an atom's mass, but it pointed the way to the existence of other particles within an atom. First of all, there had to be a positive charge to offset that of the electron, and secondly, the item or items providing this positive charge had to account for the majority of the atom's mass.

Early in the twentieth century, Thomson's student Ernest Rutherford (1871-1937) discovered that the atom has a nucleus, a center around which electrons move, and that the nucleus contains positively charged particles called protons. Protons have a mass 1,836 times as great as that of an electron, and thus seemed to account for the total atomic mass. Later, however, Rutherford and English chemist Frederick Soddy (1877-1956) discovered that when an atom emitted certain types of particles, its atomic mass changed.

**Isotopes and atomic mass.** Rutherford and Soddy named these atoms of differing mass isotopes, though at that point—because the neutron had yet to be discovered—

they did not know exactly what had caused the change in mass. Certain types of isotopes, Soddy and Rutherford concluded, had a tendency to decay, moving (sometimes over a great period of time) toward stabilization. Such isotopes were radioactive.

Soddy concluded that atomic mass, as measured by Berzelius, was actually an average of the mass figures for all isotopes within that element. This explained a problem with Mendeleev's periodic table, in which there seemed to be irregularities in the increase of atomic mass from element to element. The answer to these variations in mass, it turned out, related to the number of isotopes associated with a given element: the greater the number of isotopes, the more these affected the overall measure of the element's mass.

**A NEW DEFINITION OF ATOMIC NUMBER.** Up to this point, the term "atomic number" had a different, much less precise, meaning than it does today. As we have seen, the early twentieth century periodic table listed elements in order of their atomic mass in relation to hydrogen, and thus atomic number referred simply to an element's position in this ordering. Then, just a few years after Rutherford and Soddy discovered isotopes, Welsh physicist Henry Moseley (1887-1915) determined that every element has a unique number of protons in its nucleus.

Today, the number of protons in the nucleus, rather than the mass of the atom, determines the atomic number of an element. Carbon, for instance, has an atomic number of 6, not because there are five elements lighter—though this is also true—but because it has six protons in its nucleus. The ordering by atomic number happens to correspond to the ordering by atomic mass, but atomic number provides a much more precise means of distinguishing elements. For one thing, atomic number is always a whole integer—1 for hydrogen, for instance, or 17 for chlorine, or 92 for uranium. Figures for mass, on the other hand, are almost always rendered with decimal fractions (for example, 1.008 for hydrogen).

**NEUTRONS COMPLETE THE PICTURE.** As with many other discoveries along the way to uncovering the structure of the atom, Moseley's identification of atomic number with the proton raised still more questions. In particular, if the unique number of protons identified an element, what was it that made isotopes of the same element different from one another? Hydrogen, as it turned out, indeed had a mass very nearly equal to that of one proton—thus justifying its designation as the basic unit of atomic mass. Were it not for the isotope known as deuterium, which has a mass nearly twice as great as that of hydrogen, the element would have an atomic mass of exactly 1 amu.

A discovery by English physicist James Chadwick (1891-1974) in 1932 finally explained what made an isotope an isotope. It was Chadwick who identified the neutron, a particle with no electric charge, which resides in the nucleus alongside the protons. In deuterium, which has one proton, one neutron, and one electron, the electron accounts for only 0.0272% of the total mass—a negligible figure. The proton, on the other hand, makes up 49.9392% of the mass. Until the discovery of the neutron, there had been no explanation of the other 50.0336% of the mass in an atom with just one proton and one electron.

## Average Atomic Mass Today

Thanks to Chadwick's discovery of the neutron, it became clear why deuterium weighs almost twice as much as ordinary hydrogen. This in turn is the reason why a large sample of hydrogen, containing as it does a few molecules of deuterium here and there, does not have the same average atomic mass as a proton. Today scientists know that there are literally thousands of isotopes—many of them stable, but many more of them unstable or radioactive—for the 100-plus elements on the periodic table. Each isotope, of course, has a slightly different atomic mass. This realization has led to clarification of atomic mass figures.

One might ask how figures of atomic mass are determined. In the past, as we have seen, it was largely a matter of guesswork, but today chemists and physicist use a highly sophisticated instrument called a mass spectrometer. First, atoms are vaporized, then changed to positively charged ions, or cations, by "knocking off" electrons. The cations are then passed through a magnetic field, and this causes them to be deflected by specific amounts, depending on the size of the charge and its atomic mass. The particles eventually wind up on a deflector plate, where the amount of deflection can be measured and compared with the charge. Since 1 amu has

been calculated to equal approximately 931.494 MeV, or mega electron-volts, very accurate figures can be determined.

**Calibration of the atomic mass unit.** When 1 is divided by Avogadro's number, the result is $1.66 \cdot 10^{-24}$—the value, in grams, of 1 amu. However, in accordance with a 1960 agreement among members of the international scientific community, measurements of atomic mass take as their reference point the mass of carbon-12. Not only is the carbon-12 isotope found in all living things, but hydrogen is a problematic standard because it bonds so readily with other elements. According to the 1960 agreement, 1 amu is officially 1/12 the mass of a carbon-12 atom, whose exact value (retested in 1998), is $1.6653873 \cdot 10^{-24}$ g.

Carbon-12, sometimes represented as ${}^{12}_{6}C$, contains six protons and six neutrons. (As explained in the essay on Isotopes, where an isotope is indicated, the number to the upper left of the chemical symbol indicates the total number of protons and neutrons. Sometimes this is the only number shown; but if a number is included on the lower left, this indicates only the number of protons, which remains the same for each element.) The value of 1 amu thus obtained is, in effect, an average of the mass for a proton and neutron—a usable figure, given the fact that a neutron weighs only 0.163% more than a proton.

Of all the carbon found in nature (as opposed to radioactive isotopes created in laboratories), 98.89% of it is carbon-12. The remainder is mostly carbon-13, with traces of carbon-14, an unstable isotope produced in nature. By definition, carbon-12 has an atomic mass of exactly 12 amu; that of carbon-13 (about 1.11% of all carbon) is 13 amu. Thus the atomic mass of carbon, listed on the periodic table as 12.01 amu, is obtained by taking 98.89% of the mass of carbon-12, combined with 1.11% of the mass of carbon-13.

**Atomic mass units and the periodic table.** The periodic table as it is used today includes figures, in atomic mass units, for the average mass of each atom. As it turns out, Berzelius was not so far off in his use of hydrogen as a standard, since its mass is almost exactly 1 amu—but not quite, because (as noted above) deuterium increases the average mass somewhat. Figures increase from there along the periodic table, though not by a regular pattern. Sometimes the increase from one element to the next is by just over 1 amu, and in other cases, the increase is by more than 3 amu. This only serves to prove that atomic number, rather than atomic mass, is a more straightforward means of ordering the elements.

Mass figures for many elements that tend to appear in the form of radioactive isotopes are usually shown in parentheses. This is particularly true for elements with atomic numbers above 92, because samples of these elements do not stay around long enough to be measured. Some have a half-life—the period in which half the isotopes decay to a stable form—of just a few minutes, and for others, the half-life is but a fraction of a second. Therefore, atomic mass figures represent the mass of the longest-lived isotope.

## Uses of Atomic Mass in Chemistry

**Molar mass.** Just as the value of atomic mass units has been calibrated to the mass of carbon-12, the mole is no longer officially defined in terms of Avogadro's number, though in general its value has not changed. By international scientific agreement, the mole equals the number of carbon atoms in 12.01 g of carbon. Note that, as stated earlier, carbon has an average atomic mass of 12.01 amu.

This is no coincidence, of course: multiplication of the average atomic mass by Avogadro's number yields a figure in grams equal to the value of the average atomic mass in amu. A mole of helium, with an average atomic mass of 4.003, is 4.003 g. Iron, on the other hand, has an average atomic mass of 55.85, so a mole of iron is 55.85 g. These figures represent the molar mass—the mass of 1 mole—for each of the elements mentioned.

**The need for exact proportions.** When chemists discover new substances in nature or create new ones in the laboratory, the first thing they need to determine is the chemical formula—in other words, the exact quantities and proportions of elements in each molecule. By chemical means, they separate the compound into its constituent elements, then determine how much of each element is present.

## KEY TERMS

**ATOM:** The smallest particle of an element that retains all the chemical and physical properties of that element.

**ATOMIC MASS UNIT:** An SI unit (abbreviated amu), equal to $1.66 \cdot 10^{-24}$ 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 of elements in order of atomic number.

**ATOMIC WEIGHT:** An old term for atomic mass. Since weight varies depending on gravitational field, whereas mass is the same throughout the universe, scientists typically use the term "atomic mass" instead.

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

**AVOGADRO'S NUMBER:** A figure, named after Italian physicist Amedeo Avogadro (1776-1856), equal to $6.022137 \times 10^{23}$. Avogadro's number indicates the number of atoms or molecules in a mole.

**COMPOUND:** A substance made up of atoms of more than one element. These atoms are usually joined in molecules.

**DALTON:** An alternate term for atomic mass units, used in biochemistry and microbiology for describing the mass of large organic molecules. The dalton (abbreviated Da or D) is named after English chemist John Dalton (1766-1844), who introduced the concept of the atom to science.

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

**HALF-LIFE:** The length of time it takes a substance to diminish to one-half its initial amount.

Since they are using samples in relatively large quantities, molar mass figures for each element make it possible to determine the chemical composition. To use a very simple example, suppose a quantity of water is separated, and the result is 2.016 g of hydrogen and 16 g of oxygen. The latter is the molar mass of oxygen, and the former is the molar mass of hydrogen multiplied by two. Thus we know that there are two moles of hydrogen and one mole of oxygen, which combine to make one mole of water.

Of course the calculations used by chemists working in the research laboratories of universities, government institutions, and corporations are much, much more complex than the example we have given. In any case, it is critical that a chemist be exact in making these determinations, so as to know the amount of reactants needed to produce a given amount of product, or the amount of product that can be produced from a given amount of reactant.

When a company produces millions or billions of a single item in a given year, a savings of very small quantities in materials—thanks to proper chemical measurement—can result in a savings of billions of dollars on the bottom line. Proper chemical measurement can also save lives. Again, to use a very simple example, if a mole of compounds weighs 44.01 g and is found to contain two moles of oxygen and one of carbon, then it is merely carbon dioxide—a compound essential to plant life. But if it weighs 28.01 g and has one mole of oxygen with one mole of carbon, it is poisonous carbon monoxide.

## KEY TERMS CONTINUED

**ION:** An atom or group of atoms that has lost or gained one or more electrons, and thus has a net electric charge.

**ISOTOPES:** Atoms of the same element (that is, they have the same number of protons) that differ in terms of mass. Isotopes may be either stable or unstable. The latter type, known as radioisotopes, are radioactive.

**MASS:** The amount of matter an object contains.

**MOLAR MASS:** The mass, in grams, of 1 mole of a given substance. The value in grams of molar mass is always equal to the value, in atomic mass units, of the average atomic mass of that substance. Thus carbon has a molar mass of 12.01 g, and an average atomic mass of 12.01 amu.

**MOLE:** The SI fundamental unit for "amount of substance." A mole is, generally speaking, Avogadro's number of atoms or molecules; however, in the more precise SI definition, a mole is equal to the number of carbon atoms in 12.01 g of carbon.

**MOLECULE:** A group of atoms, usually, but not always, representing more than one element, joined in a structure. Compounds are typically made of up molecules.

**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 (in atomic mass units) for that particular element.

**RADIOACTIVITY:** A term describing a phenomenon whereby certain isotopes known as radioisotopes are subject to a form of decay brought about by the emission of high-energy particles. "Decay" does not mean that the isotope "rots"; rather, it decays to form another isotope, until eventually (though this may take a long time), it becomes stable.

## WHERE TO LEARN MORE


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# ELECTRONS

## CONCEPT

No one can see an electron. Even an electron microscope, used for imaging the activities of these subatomic particles, does not offer a glimpse of an electron as one can look at an amoeba; instead, the microscope detects the patterns of electron deflection. In any case, a single-cell organism is gargantuan in comparison to an electron. Even when compared to a proton or a neutron, particles at the center of an atom, electrons are minuscule, being slightly more than 1/2000 the size of either. Yet the electron is the key to understanding the chemical process of bonding, and electron configurations clarify a number of aspects of the periodic table that may, at first, seem confusing.

## HOW IT WORKS

### The Electron's Place in the Atom

The atom is discussed in detail elsewhere in this book; here, the particulars of atomic structure will be presented in an abbreviated form, so that the discussion of electrons may proceed. At the center of an atom, the smallest particle of an element, there is a nucleus, which contains protons and neutrons. Protons are positive in charge, while neutrons exert no charge.

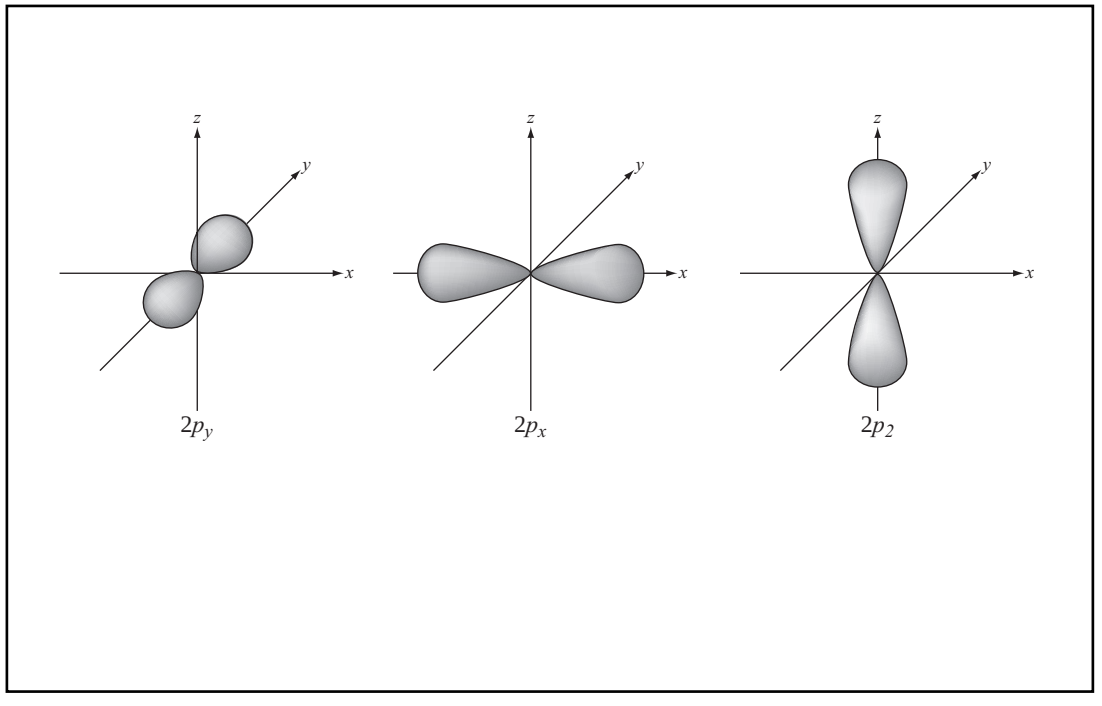
Moving around the nucleus are electrons, negatively charged particles whose mass is very small in comparison to the proton or neutron: 1/1836 and 1/1839 the mass of the proton and neutron respectively. The mass of an electron is $9.109389 \cdot 10^{-33}$ g. Compare the number 9 to the number 1,000,000,000,000,000,000,000,000,000,000,000, and this gives some idea of the ratio between an electron's mass and a gram. The large number—1 followed by 33 zeroes—is many trillions of times longer than the age of the universe in seconds.

**IONS AND CHEMICAL BONDS.** Electrons, though very small, are exceedingly powerful, and they are critical to both physical and chemical processes. The negative charge of an electron, designated by the symbol 1- or -1, is enough to counteract the positive charge (1+ or +1) of a proton, even though the proton has much greater mass. As a result, atoms (because they possess equal numbers of protons and electrons) have an electric charge of zero.

Sometimes an atom will release an electron, or a released electron will work its way into the structure of another atom. In either case, an atom that formerly had no electric charge acquires one, becoming an ion. In the first of the instances described, the atom that has lost an electron or electrons becomes a positively charged ion, or cation. In the second instance, an atom that gains an electron or electrons becomes a negatively charged ion, or anion.

One of the first forms of chemical bonding discovered was ionic bonding, in which electrons clearly play a role. In fact, electrons are critical to virtually all forms of chemical bonding, which relates to the interactions between electrons of different atoms.

**MOVEMENT OF THE ELECTRON ABOUT THE NUCLEUS.** If the size of the nucleus were compared to a grape, the edge of the atom itself would form a radius of about a mile. Because it is much smaller than the nucle-




TWO-LOBED ORBITALS.

us, an electron might be depicted in this scenario as a speck of dust—but a speck of dust with incredible energy, which crosses the mile radius of this enlarged atom at amazing speeds. In an item of matter that has been frozen to absolute zero, an electron moves relatively little. On the other hand, it can attain speeds comparable to that of the speed of light: 186,000 mi (299,339 km) per second.

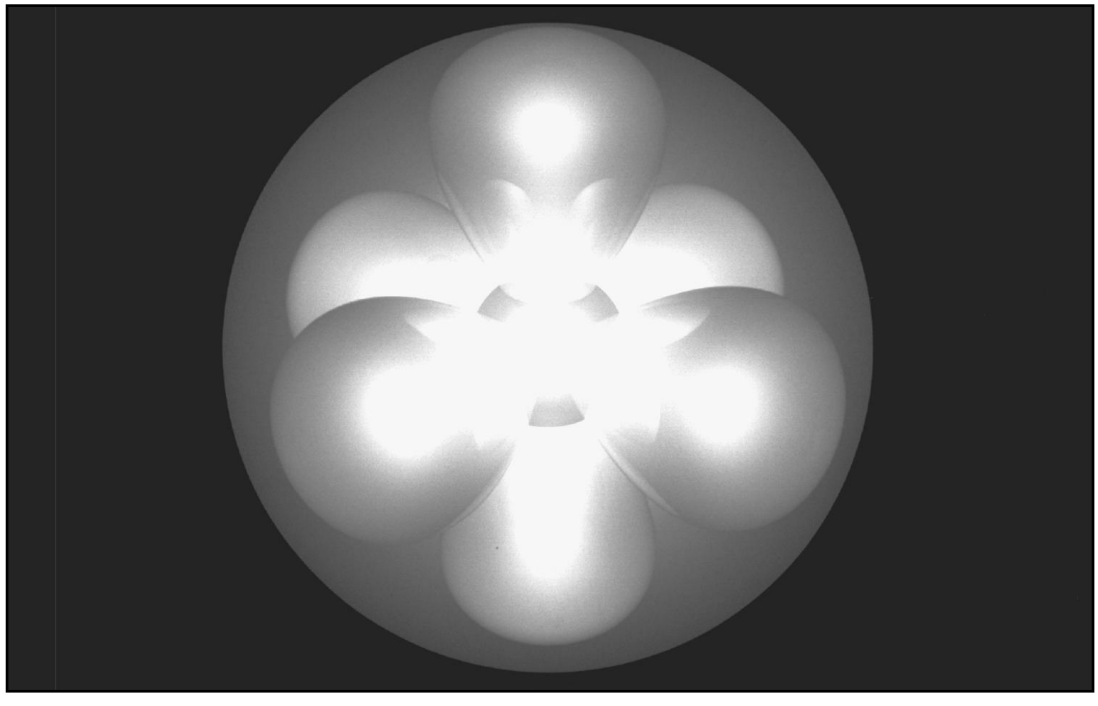
The electron does not move around the nucleus as a planet orbits the Sun—a model of electron behavior that was once accepted, but which has since been overturned. On the other hand, as we shall see, the electron does not simply "go where it pleases": it acts in accordance with complex patterns described by the quantum theory of physics. Indeed, to some extent the behavior of the electron is so apparently erratic that the word "pattern" seems hardly to describe it. However, to understand the electron clearly, one has to set aside all ideas about how objects behave in the physical world.

## Emerging Models of Electron Behavior

The idea that matter is composed of atoms originated in ancient Greece, but did not take hold until early in the nineteenth century, with the atomic theory of English chemist John Dalton (1766-1844). In the years that followed, numerous figures—among them Russian chemist Dmitri Mendeleev (1834-1907), father of the periodic table of elements—contributed to the emerging understanding of the atomic model.

Yet Mendeleev, despite his awareness that the mass of an atom differentiated one element from another, had no concept of subatomic particles. No one did: until very late in the nineteenth century, the atom might as well have been a hard-shelled ball of matter, for all that scientists understood about its internal structure. The electron was the first subatomic particle discovered, in 1897—nearly a century after the scientific beginning of atomic theory. Yet the first hints regarding its existence had begun to appear some 60 years before.

**DISCOVERY OF THE ELECTRON.** In 1838, British physicist and chemist Michael Faraday (1791-1867) was working with a set of electrodes—metal plates used to emit or collect electric charge—which he had placed at either end of an evacuated glass tube. (In other words, most of the air and other matter had been removed from the tube.) He applied a charge of several thousand volts between the electrodes, and discovered that an electric current flowed between them.



A computer-generated model of a neon atom. The nucleus, at center, is too small to be seen at this scale and is represented by the flash of light. Surrounding the nucleus are the atom's electron orbitals: 1s (small sphere), 2s (large sphere), and 2p (lobed). *(Photograph by Kenneth Eward/BioGrafx. National Audubon Society Collection/Photo Researchers, Inc. Reproduced by permission.)*

This seemed to suggest the existence of particles carrying an electric charge, and four decades later, English physicist William Crookes (1832-1919) expanded on these findings with his experiments using an apparatus that came to be known as a Crookes tube. As with Faraday's device, the Crookes tube used an evacuated glass tube encased between two electrodes—a cathode at the negatively charged end, and an anode at the positively charged end. A wire led outside the bulb to an electric source, and when electricity was applied to the electrodes, the cathodes emitted rays. Crookes concluded that the cathode rays were particles with a negative electric charge that came from the metal in the cathode plate.

English physicist J. J. Thomson (1856-1940) hypothesized that the negatively charged particles Crookes had observed were being emitted by atoms, and in 1897 he gave a name to these particles: electrons. The discovery of the electron raised questions concerning its place in the atom: obviously, there had to be a counterbalancing positive charge, and if so, from whence did it come?

**FROM PLUM PUDDINGS TO PLANETS.** Around the beginning of the twentieth century, the prevailing explanation of atomic structure was the "plum pudding model," which depicted electrons as floating like raisins in a "pudding" of positive charges. This was overturned by the discovery of the nucleus, and, subsequently, of the proton and neutron it contained.

In 1911, the great Danish physicist Niels Bohr (1885-1962) studied hydrogen atoms, and concluded that electrons move around the nucleus in much the same way that planets move around the Sun. This worked well when describing the behavior of hydrogen, which, in its simplest form—the isotope protium—has only one electron and one proton, without any neutrons. The model did not work as well when applied to other elements, however, and within less than two decades Bohr's planetary model was overturned.

As it turns out, the paths of an electron's movement around the nucleus are nothing like that of a planet's orbit—except inasmuch as both models describe a relatively small object moving around a relatively large one. The reality is much more complex, and to comprehend the secret of the electron's apparently random behavior is

truly a mind-expanding experience. Yet Bohr is still considered among the greatest scientists of the twentieth century: it was he, after all, who first explained the quantum behavior of electrons, examined below.

## REAL-LIFE APPLICATIONS

### Quantum Theory and the Atom

Much of what scientists understand today about the atom in general, and the electron in particular, comes from the quantum theory introduced by German physicist Max Planck (1858-1947). Planck showed that, at the atomic level, energy is emitted in tiny packets, or "quanta." Applying this idea to the electron, Bohr developed an idea of the levels at which an electron moves around the nucleus. Though his conclusions led him to the erroneous planetary model, Bohr's explanation of energy levels still prevails.

As has been suggested, the interaction between electrons and protons is electromagnetic, and electromagnetic energy is emitted in the form of radiation, or a stream of waves and particles. The Sun, for instance, emits electromagnetic radiation along a broad spectrum that includes radio waves, infrared light, visible light, ultraviolet light, x rays, and gamma rays. These are listed in ascending order of their energy levels, and the energy emitted can be analyzed in terms of wavelength and frequency: the shorter the wavelength, the greater the frequency and the greater the energy level.

When an atom is at its ordinary energy level, it is said to be in a ground state, but when it acquires excess energy, it is referred to as being in an excited state. It may release some of that energy in the form of a photon, a particle of electromagnetic radiation. The amount of energy involved can be analyzed in terms of the wavelengths of light the atom emits in the form of photons, and such analysis reveals some surprising things about the energy levels of atoms.

If one studies the photons emitted by an atom as it moves between a ground state and an excited state, one discovers that it emits only certain kinds of photons. From this, Bohr concluded that the energy levels of an atom do not exist on a continuum; rather, there are only certain energy levels possible for an atom of a given element. The energy levels are therefore said to be quantized.

### The Wave Mechanical Model

In everyday terms, quantization can be compared to the way that a person moves up a set of stairs: by discrete steps. If one step directly follows another, there is no step in between, nor is there any gradual way of moving from step to step, as one would move up a ramp. The movement of electrons from one energy level to another is not a steady progression, like the movement of a person up a ramp; rather, it is a series of quantum steps, like those a person makes when climbing a set of stairs.

The idea of quantization was ultimately applied to describing the paths that an electron makes around the nucleus, but this required some clarification along the way. It had been believed that an electron could move through any point between the nucleus and the edge of the atom (again, like a ramp), but it later became clear that the electrons could only move along specific energy levels. As we have seen, Bohr believed that these corresponded to the orbits of planets around the Sun; but this explanation would be discarded in light of new ideas that emerged in the 1920s.

During the early part of that decade, French physicist Louis de Broglie (1892-1987) and Austrian physicist Erwin Schrödinger (1887-1961) introduced what came to be known as the wave mechanical model, also known as the particle-wave hypothesis. Because light appeared to have the properties of both particles and waves, they reasoned, electrons (possessing electromagnetic energy as they did) might behave in the same fashion. In other words, electrons were not just particles: in some sense, they were waves as well.

**UNDERSTANDING ORBITALS.** The wave mechanical model depicted the movement of electrons, not as smooth orbits, but as orbitals—regions in which there is the highest probability that an electron will be found. An orbital is nothing like the shape of a solar system, but, perhaps ironically, it can be compared to the photographs astronomers have taken of galaxies. In most of these photographs, one sees an area of

intense light emitted by the stars in the center. Further from this high-energy region, the distribution of stars (and hence of light) becomes increasingly less dense as one moves from the center of the galaxy to the edges.

Replace the center of the galaxy with the nucleus of the atom, and the stars with electrons, and this is an approximation of an orbital. Just as a galaxy looks like a cloud of stars, scientists use the term electron cloud to describe the pattern formed by orbitals. The positions of electrons cannot be predicted; rather, it is only possible to assign probabilities as to where they will be. Naturally, they are most drawn to the positive charges in the nucleus, and hence an orbital depicts a high-density region of probabilities at the center—much like the very bright center of a galaxy.

The further away from the nucleus, the less the probability that an electron will be in that position. Hence in models of an orbital, the dots are concentrated at the center, and become less dense the further away from the nucleus they are. As befits the comparison to a cloud, the edge of an orbital is fuzzy. Contrary to the earlier belief that an atom was a clearly defined little pellet of matter, there is no certainty regarding the exact edge of a given atom; rather, scientists define the sphere of the atom as the region encompassing 90% of the total electron probability.

**THE MYSTERIOUS ELECTRON.** As complex as this description of electron behavior may seem, one can rest assured that the reality is infinitely more complex than this simplified explanation suggests. Among the great mysteries of the universe is the question of why an electron moves as it does, or even exactly how it does so. Nor does a probability model give us any way of knowing when an electron will occupy a particular position.

In fact, as German physicist Werner Heisenberg (1901-1976) showed with what came to be known as the Heisenberg Uncertainty Principle, it is impossible to know both the speed of an electron and its precise position at the same time. This, of course, goes against every law of physics that prevailed until about 1920, and in fact quantum theory offers an entirely different model of reality than the one accepted during the seventeenth, eighteenth, and nineteenth centuries.

## ORBITALS

Given the challenges involved in understanding electron behavior, it is amazing just how much scientists do know about electrons—particularly where energy levels are concerned. This, in turn, makes possible an understanding of the periodic table that would astound Mendeleev.

Every element has a specific configuration of energy levels that becomes increasingly complex as one moves along the periodic table. In the present context, these configurations will be explained as simply as possible, but the reader is encouraged to consult a reliable chemistry textbook for a more detailed explanation.

**PRINCIPAL ENERGY LEVELS AND SUBLEVELS.** The principal energy level of an atom indicates a distance that an electron may move away from the nucleus. This is designated by a whole-number integer, beginning with 1 and moving upward: the higher the number, the further the electron is from the nucleus, and hence the greater the energy in the atom. Each principal energy level is divided into sublevels corresponding to the number *n* of the principal energy level: thus principal energy level 1 has one sublevel, principal energy level 2 has two, and so on.

The simplest imaginable atom, a hydrogen atom in a ground state, has an orbital designated as $1s^1$. The *s* indicates that an electron at energy level 1 can be located in a region described by a sphere. As for the significance of the superscript 1, this will be explained shortly.

Suppose the hydrogen atom is excited enough to be elevated to principal energy level 2. Now there are two sublevels, 2*s* (for now we will dispense with the superscript 1) and 2*p*. A *p* orbital is rather like the shape of a figure eight, with its center of gravity located on the nucleus, and thus unlike the *s* sublevel, *p* orbitals can have a specific directional orientation. Depending on whether it is oriented along an *x*-, *y*-, or *z*-axis, orbitals in sublevel *p* are designated as $2p_x$, $2p_y$, or $2p_z$.

If the hydrogen atom is further excited, and therefore raised to principal energy level 3, it now has three possible sublevels, designated as *s*, *p*, and *d*. Some of the *d* orbitals can be imagined as two figure eights at right angles to one another, once again with their centers of gravity along the nucleus of the atom. Because of their more com-

plex shape, there are five possible spatial orientations for orbitals at the *d* sublevel.

Even more complex is the model of an atom at principal level 4, with four sublevels—*s*,*p*, *d*, and *f*, which has a total of seven spatial orientations. Obviously, things get very, very complex at increased energy levels. The greater the energy level, the further the electron can move from the nucleus, and hence the greater the possible number of orbitals and corresponding shapes.

**ELECTRON SPIN AND THE PAULI EXCLUSION PRINCIPLE.** Every electron spins in one of two directions, and these are indicated by the symbols ↑ and ↓. According to the Pauli exclusion principle, named after the Austrian-Swiss physicist Wolfgang Pauli (1900-1958), no more than two electrons can occupy the same orbital, and those two electrons must have spins opposite one another.

This explains the use of the superscript 1, which indicates the number of electrons in a given orbital. This number is never greater than two: hence, the electron configuration of helium is written as $1s^2$. It is understood that these two electrons must be spinning in opposite directions, but sometimes this is indicated by an orbital diagram showing both an upward- and downward-pointing arrow in an orbital that has been filled, or only an upward-pointing arrow in an orbital possessing just one electron.

## Electron Configuration and the Periodic Table

**THE FIRST 18 ELEMENTS.** As one moves up the periodic table from atomic number 1 (hydrogen) to 18 (argon), a regular pattern emerges. The orbitals are filled in a neat progression: from helium (atomic number 2) onward, all of principal level 1 is filled; beginning with beryllium (atomic number 4), sublevel 2*s* is filled; from neon (atomic number 10), sublevel 2*p*—and hence principal level 2 as a whole—is filled, and so on. The electron configuration for neon, thus, is written as $1s^2 2s^2 2p^6$.

Note that if one adds together all the superscript numbers, one obtains the atomic number of neon. This is appropriate, of course, since atomic number is defined by the number of protons, and an atom in a non-ionized state has an equal number of protons and electrons. In noticing the electron configurations of an element, pay close attention to the last or highest principal energy level represented. These are the valence electrons, the ones involved in chemical bonding. By contrast, the core electrons, or the ones that are at lower energy levels, play no role in the bonding of atoms.

**SHIFTS IN ELECTRON CONFIGURATION PATTERNS.** After argon, however, as one moves to the element occupying the nineteenth position on the periodic table—potassium—the rules change. Argon has an electron configuration of $1s^2 2s^2 2p^6 3s^2 3p^6$, and by the pattern established with the first 18 elements, potassium should begin filling principal level 3*d*. Instead, it "skips" 3*d* and moves on to 4*s*. The element following argon, calcium, adds a second electron to the 4*s* level.

After calcium, the pattern again changes. Scandium (atomic number 21) is the first of the transition metals, a group of elements on the periodic table in which the 3*d* orbitals are filled. This explains why the transition metals are indicated by a shading separating them from the rest of the elements on the periodic table.

But what about the two rows at the very bottom of the chart, representing groups of elements that are completely set apart from the periodic table? These are the lanthanide and actinide series, which are the only elements that involve *f* sublevels. In the lanthanide series, the seven 4*f* orbitals are filled, while the actinide series reflects the filling of the seven 5*f* orbitals.

As noted earlier, the patterns involved in the *f* sublevel are ultra-complex. Thus it is not surprising than the members of the lanthanide series, with their intricately configured valence electrons, were very difficult to extract from one another, and from other elements: hence their old designation as the "rare earth metals." However, there are a number of other factors—relating to electrons, if not necessarily electron configuration—that explain why one element bonds as it does to another.

**CHANGES IN ATOMIC SIZE.** With the tools provided by the basic discussion of electrons presented in this essay, the reader is encouraged to consult the essays on Chemical Bonding, as well as The Periodic Table of the Elements, both of which explore the consequences of electron arrangement in chemistry. Not only are electrons the key to chemical bonding, understanding their configurations is critical to an understanding of the periodic table.

## KEY TERMS

**ANION:** The negative ion that results when an atom gains one or more electrons.

**ANODE:** An electrode at the positively charged end of a supply of electric current.

**ATOM:** The smallest particle of an element.

**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 of elements in order of atomic number.

**CATHODE:** An electrode at the negatively charged end of a supply of electric current.

**CATION:** The positive ion that results when an atom loses one or more electrons.

**ELECTRODE:** A structure, often a metal plate or grid, that conducts electricity, and which is used to emit or collect electric charge.

**ELECTRON:** A negatively charged particle in an atom.

**ELECTRON CLOUD:** A term used to describe the pattern formed by orbitals.

**EXCITED STATE:** A term describing the characteristics of an atom that has acquired excess energy.

**GROUND STATE:** A term describing the state of an atom at its ordinary energy level.

**ION:** An atom or atoms 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.

**NEUTRON:** A subatomic particle that has no electric charge. Neutrons are found in 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.

One of the curious things about the periodic table, for instance, is the fact that the sizes of atoms decrease as one moves from left to right across a row or period, even though the sizes increase as one moves from top to bottom along a column or group. The latter fact—the increase of atomic size in a group, as a function of increasing atomic number—is easy enough to explain: the higher the atomic number, the higher the principal energy level, and the greater the distance from the nucleus to the furthest probability range.

On the other hand, the decrease in size across a period (row) is a bit more challenging to comprehend. However, all the elements in a period have their outermost electrons at a particular principal energy level corresponding to the number of the period. For instance, the elements on period 5 all have principal energy levels 1 through 5. Yet as one moves along a period from left to right, there is a corresponding increase in the number of protons within the nucleus. This means a stronger positive charge pulling the electrons inward; therefore, the "electron cloud" is drawn ever closer toward the increasingly powerful charge at the center of the atom.

### WHERE TO LEARN MORE

"*Chemical Bond*" (Web site). <http://www.science.uwaterloo.ca/~cchieh/cact/c120/chembond.html> (May 18, 2001).

"*The Discovery of the Electron*" (Web site). <http://www.aip.org/history/electron/> (May 18, 2001).

## KEY TERMS CONTINUED

**ORBITAL:** A pattern of probabilities regarding the regions that an electron can occupy within an atom in a particular energy state. The orbital, complex and imprecise as it may seem, is a much more accurate depiction of electron behavior than the model once used, which depicted electrons moving in precisely defined orbits around the nucleus, rather as planets move around the Sun.

**PERIODIC TABLE OF ELEMENTS:** A chart that shows the elements arranged in order of atomic number. Vertical columns within the periodic table indicate groups or "families" of elements with similar chemical characteristics.

**PHOTON:** A particle of electromagnetic radiation.

**PRINCIPAL ENERGY LEVEL:** A value indicating the distance that an electron may move away from the nucleus of an atom. This is designated by a whole-number integer, beginning with 1 and moving upward. The higher the number, the further the electron is from the nucleus, and hence the greater the energy in the atom.

**PROTON:** A positively charged particle in an atom.

**QUANTIZATION:** A term describing any property that has only certain discrete values, as opposed to values distributed along a continuum. The quantization of an atom means that it does not have a continuous range of energy levels; rather, it can exist only at certain levels of energy from the ground state through various excited states.

**RADIATION:** In a general sense, radiation can refer to anything that travels in a stream, whether that stream be composed of subatomic particles or electromagnetic waves.


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# ISOTOPES

## CONCEPT

Isotopes are atoms of the same element that have different masses due to differences in the number of neutrons they contain. Many isotopes are stable, meaning that they are not subject to radioactive decay, but many more are radioactive. The latter, also known as radioisotopes, play a significant role in modern life. Carbon-14, for instance, is used for estimating the age of objects within a relatively recent span of time—up to about 5,000 years—whereas geologists and other scientists use uranium-238 to date minerals of an age on a scale with that of the Earth. Concerns over nuclear power and nuclear weapons testing in the atmosphere have heightened awareness of the dangers posed by certain kinds of radioactive isotopes, which can indeed be hazardous to human life. However, the reality is that people are subjected to considerably more radiation from nonnuclear sources.

## HOW IT WORKS

### Atoms and Elements

The elements are substances that cannot be broken down into other matter by chemical means, and an atom is the fundamental particle in an element. As of 2001, there were 112 known elements, 88 of which occur in nature; the rest were created in laboratories. Due to their high levels of radioactivity, they exist only for extremely short periods of time. Whatever the number of elements—and obviously that number will increase over time, as new elements are synthesized—the same number of basic atomic structures exists in the universe.

What distinguishes one element from another is the number of protons, subatomic particles with a positive electric charge, in the nucleus, or center, of the atom. The number of protons, whatever it may be, is unique to an element. Thus if an atom has one proton, it is an atom of hydrogen, because hydrogen has an atomic number of 1, as shown on the periodic table of elements. If an atom has 109 protons, on the other hand, it is meitnerium. (Meitnerium, synthesized at a German laboratory in 1982, is the last element on the periodic table to have been assigned a name as of 2001.)

**THE NUCLEUS AND ELECTRONS.** Together with protons in the nucleus are neutrons, which exert no charge. The discovery of these particles, integral to the formation of isotopes, is discussed below. The nucleus, with a diameter about 1/10,000 that of the atom itself, makes up only a tiny portion of the atom's volume, but the vast majority of its mass. Thus a change in the mass of a nucleus, as occurs when an isotope is formed, is reflected by a noticeable change in the mass of the atom itself.

Far from the nucleus (in relative terms, of course), at the perimeter of the atom, are the electrons, which have a negative electric charge. Whereas the protons and neutrons have about the same mass, the mass of an electron is less than 0.06% of either a proton or neutron. Nonetheless, electrons play a highly significant role in chemical reactions and chemical bonding. Just as isotopes are the result of changes in the number of neutrons, ions—atoms that are either positive or negative in electric charge—are the result of changes in the number of electrons.

Unless it loses or gains an electron, thus becoming an ion, an atom is neutral in charge, and it maintains this electric-charge neutrality by having an equal number of protons and electrons. There is, however, no law of the universe stating that an atom must have the same number of neutrons as it does protons and electrons: some do, but this is far from universal, as we shall see.

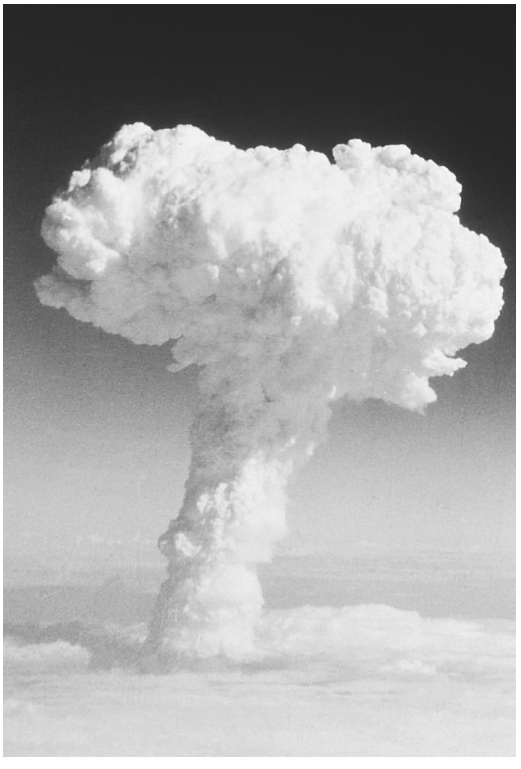
## NEUTRONS

The number of neutrons is variable within an element precisely because they exert no charge, and thus while their addition or removal changes the mass, it does not affect the electric charge of the atom. Therefore, whereas the importance of the proton and the electron is very clear to anyone who studies atomic behavior, neutrons, on the other hand, might seem at first glance as though they are only "along for the ride." Yet they are all-important to the formation of isotopes.

Not surprisingly, given their lack of electric charge, neutrons were the last of the three major subatomic particles to be discovered. English physicist J. J. Thomson (1856-1940) identified the electron in 1897, and another English physicist, Ernest Rutherford (1871-1937), discovered the proton in 1914. Rutherford's discovery overturned the old "plum pudding" model, whereby atoms were depicted as consisting of electrons floating in a positively charged cloud, rather like raisins in an English plum pudding. As Rutherford showed, the atom must have a nucleus—yet protons alone could not account for the mass of the nucleus.

There must be something else at the heart of the atom, and in 1932, yet another English physicist, James Chadwick (1891-1974), identified what it was. Working with radioactive material, he found that a certain type of subatomic particle could penetrate lead. All types of radiation known at the time were stopped by the lead, and therefore Chadwick reasoned that this particle must be neutral in charge. In 1932, he won the Nobel Prize in physics for his discovery of the neutron.

**NEUTRONS AND NUCLEAR FUSION.** Neutrons played a critical role in the development of the atomic bomb during the 1940s. In nuclear fission, atoms of uranium are bombarded with neutrons. The result is that the uranium nucleus splits in half, releasing huge amounts of energy. As it does so, it emits several extra neutrons, which split more uranium nuclei, creating still more energy and setting off a chain reaction.

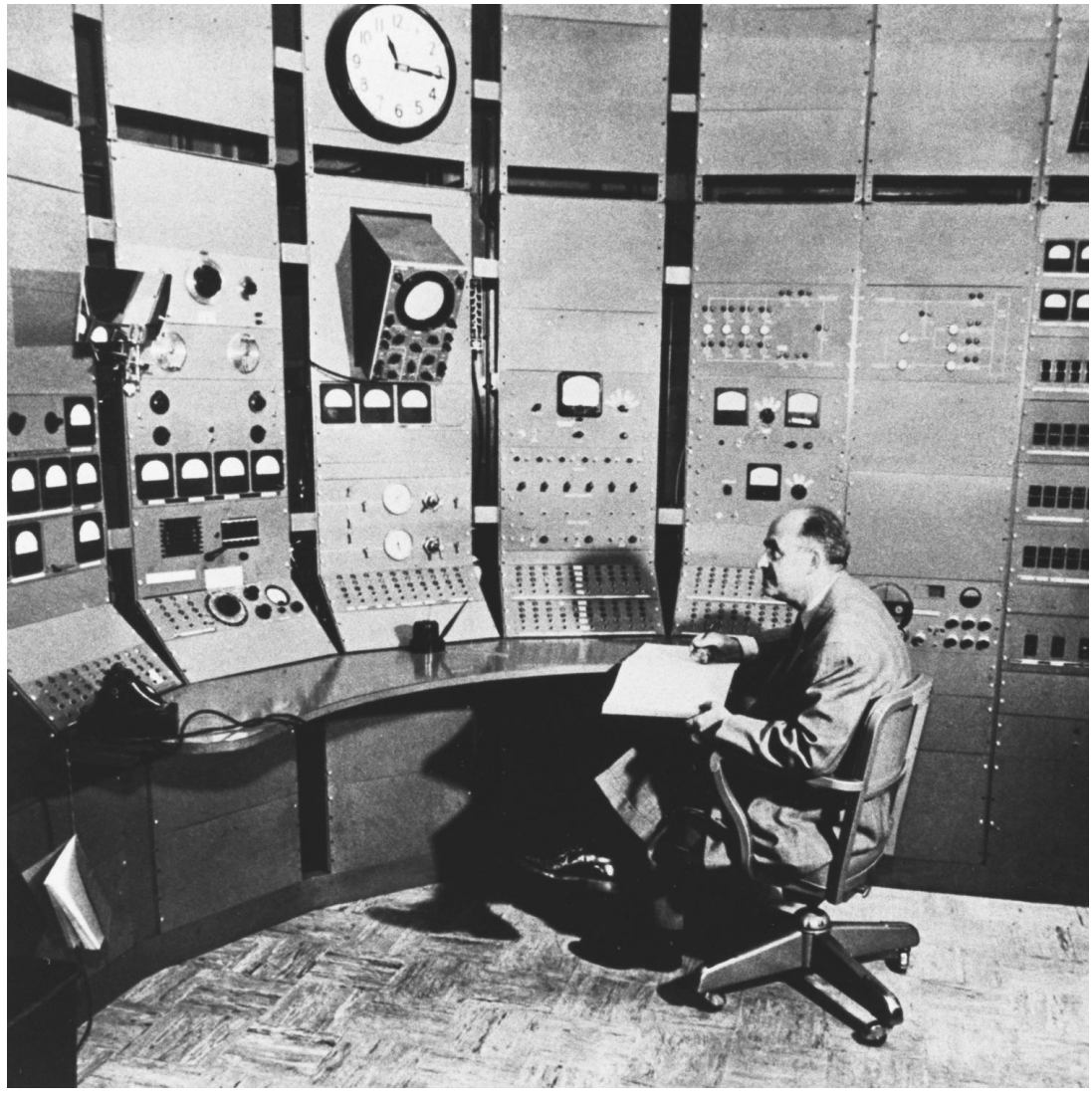


A MUSHROOM CLOUD RISES AFTER THE DETONATION OF A HYDROGEN BOMB BY FRANCE IN A 1968 TEST. DEUTERIUM IS A CRUCIAL PART OF THE DETONATING DEVICE FOR HYDROGEN BOMBS. *(Bettmann/Corbis. Reproduced by permission.)*

This explains the destructive power in an atomic bomb, as well as the constructive power—providing energy to homes and businesses—in a nuclear power plant. Whereas the chain reaction in an atomic bomb becomes an uncontrolled explosion, in a nuclear plant, the reaction is slowed and controlled. One of the means used to do this is by the application of "heavy water," which, as we shall see, is water made with a hydrogen isotope.

## ISOTOPES: THE BASICS

Two atoms may have the same number of protons, and thus be of the same element, yet differ in their number of neutrons. Such atoms are called isotopes, atoms of the same element having different masses. The name comes from the Greek phrase *isos topos*, meaning "same place": because they have the same atomic number,



Enrico Fermi.

isotopes of the same element occupy the same position on the periodic table.

Also called nuclides, isotopes are represented symbolically as follows: ${}^{m}_{a}S$, where *S* is the symbol of the element, a is the atomic number, and *m* is the mass number—the sum of protons and neutrons in the atom's nucleus. For the stable silver isotope designated as ${}^{93}_{47}Ag$, for instance, Ag is the element symbol; 47 its atomic number; and 93 the mass number. From this, it is easy to discern that this particular stable isotope has 46 neutrons in its nucleus.

Because the atomic number of any element is established, sometimes isotopes are represented simply with the mass number, thus: ${}^{93}Ag$. They may also be designated with a subscript notation indicating the number of neutrons, so that this information can be obtained at a glance without having to do the arithmetic. For the silver isotope shown here, this is written as ${}^{93}_{47}Ag_{46}$. Isotopes can also be indicated by simple nomenclature: for instance, carbon-12 or carbon-13.

## Stable and Unstable Isotopes

Radioactivity is 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 emitted in radiation 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

radiation emitted by the Sun. Radioactivity will be discussed below, but for the present, the principal concern is with radioactive properties as a distinguishing factor between the two varieties of isotope.

Isotopes are either stable or unstable. The unstable variety, known as radioisotopes, are subject to radioactive decay, but in this context, "decay" does not mean what it usually does. A radioisotope does not "rot"; it decays by turning into another isotope of the same element—or even into another element entirely. (For example, uranium-238 decays by emitting alpha particles, ultimately becoming lead-206.) A stable isotope, on the other hand, has already become what it is going to be, and will not experience further decay.

Most elements have between two and six stable isotopes. On the other hand, a few elements—for example, technetium—have no stable isotopes. Twenty elements, among them gold, fluorine, sodium, aluminum, and phosphorus, have only one stable isotope each. The element with the most stable isotopes is easy to remember because its name is almost the same as its number of stable isotopes: tin, with 10.

As for unstable isotopes, there are over 1,000, some of which exist in nature, but most of which have been created synthetically in laboratories. This number is not fixed; in any case, it is not necessarily important, because many of these highly radioactive isotopes last only for fractions of a second before decaying to form a stable isotope. Yet radioisotopes in general have so many uses, in comparison to stable isotopes, that they are often referred to simply as "isotopes."

### Understanding Isotopes

Before proceeding with a discussion of isotopes and their uses, it is necessary to address a point raised earlier, when it was stated that some atoms do have the same numbers of neutrons and protons, but that this is far from universal. In fact, nuclear stability is in part a function of neutron-to-proton ratio.

Stable nuclei with low atomic numbers (up to about 20) have approximately the same number of neutrons and protons. For example, the most stable and abundant form of carbon is carbon-12, with six protons and six neutrons. Beyond atomic number 20 or so, however, the number of neutrons begins to grow: in other words, the lowest mass number is increasingly high in comparison to the atomic number.

For example, uranium has an atomic number of 92, but the lowest mass number for a uranium isotope is not 184, or 92 multiplied by two; it is 218. The ratio of neutrons to protons necessary for a stable isotope creeps upward along the periodic table: tin, with an atomic number of 50, has a stable isotope with a mass number of 120, indicating a 1.4 to 1 ratio of neutrons to protons. For mercury-200, the ratio is 1.5 to 1.

The higher the atomic number, by definition, the greater the number of protons in the nucleus. This means that more neutrons are required to "bind" the nucleus together. In fact, all nuclei with 84 protons or more (i.e., starting at polonium and moving along the periodic table) are radioactive, for the simple reason that it is increasingly difficult for the neutrons to withstand the strain of keeping so many protons in place.

One can predict the mode of radioactive decay by noting whether the nucleus is neutron-rich or neutron-poor. Neutron-rich nuclei undergo beta emission, which decreases the numbers of protons in the nucleus. Neutron-poor nuclei typically undergo positron emission or electron capture, the first of these being more prevalent among the lighter nuclei. Elements with atomic numbers of 84 or greater generally undergo alpha emission, which decreases the numbers of protons and neutrons by two each.

## REAL-LIFE APPLICATIONS

### Deuterium and Tritium

Only three isotopes are considered significant enough to have names of their own, as opposed to being named after a parent atom (for example, carbon-12, uranium-238). These are protium, deuterium, and tritium, all three isotopes of hydrogen. Protium, or $^{1}H$, is hydrogen in its most basic form—one proton, no neutrons—and the name "protium" is only applied when necessary to distinguish it from the other two isotopes. Therefore we will focus primarily on the two others.

Deuterium, designated as $^{2}H$, is a stable isotope, whereas tritium—$^{3}H$—is radioactive. Both, in fact, have chemical symbols (D and T respec-

tively), just as though they were elements on the periodic table. What makes these two so special? They are, as it were, "the products of a good home"—in other words, their parent atom is the most basic and plentiful element in the universe. Indeed, the vast majority of the universe is hydrogen, along with helium, which is formed by the fusion of hydrogen atoms. If all atoms were numbers, then hydrogen would be 1; but of course, this is more than a metaphor, since its atomic number is indeed 1.

Ordinary hydrogen or protium, as noted, consists of a single proton and a single electron, the simplest possible atomic form possible. Its simplicity has made it a model for understanding the atom, and therefore when physicists discovered the existence of two hydrogen atoms that were just a bit more complex, they were intrigued.

Just as hydrogen represented the standard against which atoms could be measured, scientists reasoned, deuterium and tritium could offer valuable information regarding stable and unstable isotopes respectively. Furthermore, the pronounced tendency of hydrogen to bond with other substances—it almost never appears by itself on Earth—presented endless opportunities for study regarding hydrogen isotopes in association with other elements.

**ISOLATION OF DEUTERIUM.** Deuterium is sometimes called "heavy hydrogen," and its nucleus—with one proton and one neutron—is called a deuteron. It was first isolated in 1931 by American chemist Harold Clayton Urey (1893-1981), who was awarded the 1934 Nobel Prize in Chemistry for his discovery.

Serving at that time as a professor of chemistry at Columbia University in New York City, Urey started with the assumption that any hydrogen isotopes other than protium must exist in very minute quantities. This assumption, in turn, followed from an awareness that hydrogen's average atomic mass—measured in atomic mass units—was only slightly higher than 1. There must be, as Urey correctly reasoned, a very small quantity of "heavy hydrogen" on Earth.

To separate deuterium, Urey collected a relatively large sample of liquid hydrogen: 4.2 quarts (4 l). Then he allowed the liquid to evaporate very slowly, predicting that the more abundant protium would evaporate more quickly than the isotope whose existence he had hypothesized. After all but 0.034 oz (1 ml) of the sample had evaporated, he submitted the remainder to a form of analysis called spectroscopy, adding a burst of energy to the atoms and then analyzing the light spectrum they emitted for evidence of differing varieties of atom.

**CHARACTERISTICS AND USES OF DEUTERIUM.** Deuterium, with an atomic mass of 2.014102 amu, is almost exactly twice as heavy as protium, which has an atomic mass of 1.007825. Its melting point, or the temperature at which it changes from a solid to a liquid -426°F (-254°C), is much higher than for protium, which melts at -434°F (-259°C). The same relationship holds for its boiling point, or the temperature at which it changes from a liquid to its normal state on Earth, as a gas: -417°F (-249°C), as compared to -423°F (-253°C) for protium. Deuterium is also much, much less plentiful than protium: protium represents 99.985% of all the hydrogen that occurs naturally, meaning that deuterium accounts for just 0.015%.

Often, deuterium is applied as a tracer, an atom or group of atoms whose participation in a chemical, physical, or biological reaction can be easily observed. Radioisotopes are most often used as tracers, precisely because of their radioactive emissions; deuterium, on the other hand, is effective due to its almost 2:1 mass ratio in comparison to protium. In addition, it bonds with other atoms in a fashion slightly different from that of protium, and this contrast makes its presence easier to trace.

Its higher boiling and melting points mean that when deuterium is combined with oxygen to form "heavy water" ($D_2O$), the water likewise has higher boiling and melting points than ordinary water. Heavy water is often used in nuclear fission reactors to slow down the fission process, or the splitting of atoms.

**DEUTERIUM IN NUCLEAR FUSION.** Deuterium is also applied in a type of nuclear reaction much more powerful that fission: fusion, or the joining of atomic nuclei. The Sun produces energy by fusion, a thermonuclear reaction that takes places at temperatures of many millions of degrees Celsius. In solar fusion, it appears that two protium nuclei join to form a single deuteron.

During the period shortly after World War II, physicists developed a means of duplicating the thermonuclear fusion process. The result was the hydrogen bomb—more properly called a fusion bomb—whose detonating device was a compound of lithium and deuterium called lithium deuteride. Vastly more powerful than the "atomic" (that is, fission) bombs dropped by the United States over Japan in 1945, the hydrogen bomb greatly increased the threat of worldwide nuclear annihilation in the postwar years.

Yet the power that could destroy the world also has the potential to provide safe, abundant fusion energy from power plants—a dream that as yet remains unrealized. Among the approaches being attempted by physicists studying nuclear fusion is a process in which two deuterons are fused. The result is a triton, the nucleus of tritium, along with a single proton. The triton and deuteron would then be fused to create a helium nucleus, with a resulting release of vast amounts of energy.

**TRITIUM.** Whereas deuterium has a single neutron, tritium—as its mass number of 3 indicates—has two. And just as deuterium has approximately twice the mass of protium, tritium has about three times the mass, 3.016 amu. As is expected, the thermal properties of tritium are different from those of protium. Again, the melting and boiling points are higher: thus tritium heavy water ($T_2O$) melts at 40°F (4.5°C), as compared with 32°F (0°C) for $H_2O$.

Because it is radioactive, tritium is often described in terms of half-life, the length of time it takes for a substance to diminish to one-half its initial amount. The half-life of tritium is 12.26 years. As it decays, its nucleus emits a low-energy beta particle, and this results in the creation of the helium-3 isotope. Due to the low energy levels involved, the radioactive decay of tritium poses little danger to humans.

Like deuterium, tritium is applied in nuclear fusion, though due to its scarcity, it is usually combined with deuterium. Furthermore, tritium decay requires that hydrogen bombs containing the radioisotope be recharged periodically. Also, like deuterium, tritium is an effective tracer. Sometimes it is released in small quantities into groundwater as a means of monitoring subterranean water flow. It is also used as a tracer in biochemical processes.

## SEPARATING ISOTOPES

As noted in the discussion of deuterium, tritium can only be separated from protium due to the differences in mass. The chemical properties of isotopes with the same parent element make them otherwise indistinguishable, and hence purely chemical means cannot be used to separate them.

Physicists working on the Manhattan Project, the U.S. effort to develop atomic weaponry during World War II, were faced with the need to separate $^{235}U$ from $^{238}U$. Uranium-238 is far more abundant, but what they wanted was the uranium-235, highly fissionable and thus useful in the processes they were attempting.

Their solution was to allow a gaseous uranium compound to diffuse, or separate, the uranium through porous barriers. Because uranium-238 was heavier, it tended to move more slowly through the barriers, much like grains of rice getting caught in a sifter. Another means of separating isotopes is by mass spectrometry.

## RADIOACTIVITY

One of the scientists working on the Manhattan Project was Italian physicist Enrico Fermi (1901-1954), who used radium and beryllium powder to construct a neutron source for making new radioactive materials. Fermi and his associates succeeded in producing radioisotopes of sodium, iron, copper, gold, and numerous other elements. As a result of Fermi's work, for which he won the 1938 Nobel Prize in Physics, scientists have been able to develop radioactive versions of virtually all elements.

Interestingly, the ideas of radioactivity, fission reactions, and fusion reactions collectively represent the realization of a goal sought by the medieval alchemists: the transformation of one element into another. The alchemists, forerunners of chemists, believed they could transform ordinary metals into gold by using various potions—an impossible dream. Yet as noted in the preceding paragraph, among the radioisotopes generated by Fermi's neutron source was gold. The "catch," of course, is that this gold was unstable; furthermore, the amount of energy and human mental effort required to generate it far outweighed the monetary value of the gold itself.

Radioactivity is, in the modern imagination, typically associated with fallout from nuclear

war, or with hazards resulting from nuclear power—hazards that, as it turns out, have been greatly exaggerated. Nor is radioactivity always harmful to humans. For instance, with its applications in medicine—as a means of diagnosing and treating thyroid problems, or as a treatment for cancer patients—it can actually save lives.

**HAZARDS ASSOCIATED WITH RADIOACTIVITY.** It is a good thing that radiation, even the harmful variety known as ionizing radiation, is not fatal in small doses, because every person on Earth is exposed to small quantities of radiation every year. About 82% of this comes from natural sources, and 18% from manmade sources. Of course, some people are at much greater risk of radiation exposure than others: coal miners are exposed to higher levels of the radon-222 isotope present underground, while cigarette smokers ingest much higher levels of radiation than ordinary people, due to the polonium-210, lead-210, and radon-222 isotopes present in the nitrogen fertilizers used to grow tobacco.

Nuclear weapons, as most people know, produce a great deal of radioactive pollution. However, atmospheric testing of nuclear armaments has long been banned, and though the isotopes released in such tests are expected to remain in the atmosphere for about a century, they do not constitute a significant health hazard to most Americans. (It should be noted that nations not inclined to abide by international protocols might still conduct atmospheric tests in defiance of the test bans.) Nuclear power plants, despite the great deal of attention they have received from the media and environmentalist groups, do not pose the hazard that has often been claimed: in fact, coal- and oil-burning power plants are responsible for far more radioactive pollution in the United States.

This is not to say that nuclear energy poses no dangers, as the disaster at Chernobyl in the former Soviet Union has shown. In April 1986, an accident at a nuclear reactor in what is now the Ukraine killed 31 workers immediately, and ultimately led to the deaths of some 10,000 people. The fact that the radiation was allowed to spread had much to do with the secretive tactics of the Communist government, which attempted to cover up the problem rather than evacuate the area.

Another danger associated with nuclear power plants is radioactive waste. Spent fuel rods and other waste products from these plants have to be dumped somewhere, but it cannot simply be buried in the ground because it will create a continuing health hazard through the water supply. No fully fail-safe storage system has been developed, and the problem of radioactive waste poses a continuing threat due to the extremely long half-lives of some of the isotopes involved.

## Dating Techniques

In addition to their uses in applications related to nuclear energy, isotopes play a significant role in dating techniques. The latter may sound like a subject that has something to do with romance, but it does not: dating techniques involve the use of materials, including isotopes, to estimate the age of both organic and inorganic materials.

Uranium-238, for instance, has a half-life of $4.47 \cdot 10^9$ years, which is nearly the age of Earth; in fact, uranium-dating techniques have been used to determine the planet's age, which is estimated at about 4.7 billion years. As noted elsewhere in this volume, potassium-argon dating, which involves the isotopes potassium-40 and argon-40, has been used to date volcanic layers in east Africa. Because the half-life of potassium-40 is 1.3 billion years, this method is useful for dating activities that are distant in the human scale of time, but fairly recent in geological terms.

Another dating technique is radiocarbon dating, used for estimating the age of things that were once alive. All living things contain carbon, both in the form of the stable isotope carbon-12 and the radioisotope carbon-14. While a plant or animal is living, there is a certain proportion between the amounts of these two isotopes in the organism's body, with carbon-12 being far more abundant. When the organism dies, however, it ceases to acquire new carbon, and the carbon-14 present in the body begins to decay into nitrogen-14. The amount of nitrogen-14 that has been formed is thus an indication of the amount of time that has passed since the organism was alive.

Because it has a half-life of 5,730 years, carbon-14 is useful for dating activities within the span of human history, though it is not without controversy. Some scientists contend, for instance, that samples may be contaminated by carbon from the surrounding soils, thus affecting ratios and leading to inaccurate dates.

## KEY TERMS

**ATOM:** The smallest particle of an element. Atoms are made up of protons, neutrons, and electrons. Atoms that have the same number of protons—that is, are of the same element—but differ in number of neutrons are known as isotopes.

**ATOMIC MASS UNIT:** An SI unit (abbreviated amu), equal to $1.66 \cdot 10^{-24}$ 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 of elements 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.

**ELEMENT:** A substance made up of only one kind of atom. Hence an element cannot be chemically broken into other substances.

**ELECTRON:** Negatively charged particles in an atom, which spin around the protons and neutrons that make up the atom's nucleus.

**HALF-LIFE:** The length of time it takes a substance to diminish to one-half its initial amount.

**ION:** An atom or atoms 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. Isotopes may be either stable or unstable. The latter type is known as a radioisotope.

**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. The plural of "nucleus" is nuclei.

**NUCLIDES:** Another name for isotopes.

**PERIODIC TABLE OF ELEMENTS:** A chart that shows the elements arranged in order of atomic number.

**PROTON:** A positively charged particle in an atom. Protons and neutrons, which together form the nucleus around which electrons spin, have approximately the same mass—a mass that is many times greater than that of an electron. The number of protons in the nucleus of an atom is the atomic number of an element.

## KEY TERMS CONTINUED

**RADIATION:** In a general sense, radiation can refer to anything that travels in a stream, whether that stream be composed of subatomic particles or electromagnetic waves. In a more specific sense, the term relates to the radiation from radioactive materials, which can be harmful to human beings.

**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, including alpha particles, beta particles, or gamma rays.

**RADIOISOTOPE:** An isotope subject to the decay associated with radioactivity. A radioisotope is thus an unstable isotope.

**TRACER:** An atom or group of atoms whose participation in a chemical, physical, or biological reaction can be easily observed. Radioisotopes are often used as tracers.

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# IONS AND IONIZATION

## CONCEPT

Atoms have no electric charge; if they acquire one, they are called ions. Ions are involved in a form of chemical bonding that produces extremely strong bonds between metals, or between a metal and a nonmetal. These substances, of which table salt is an example, are called ionic compounds. Ionization is the process whereby electrons are removed from an atom or molecule, as well as the process whereby an ionic substance, such as salt, is dissociated into its component ions in a solution such as water. There are several varieties of ionization, including field ionization, which almost everyone has experienced in the form of static electricity. Ion exchange, or the replacement of one ion by another, is used in applications such as water purification, while chemists and physicists use ions in mass spectrometry, to discover mass and structural information concerning atoms and molecules. Another example of ions at work (and a particularly frightening example at that) is ionizing radiation, associated with the radioactive decay following a nuclear explosion.

## HOW IT WORKS

### Ions: Positive and Negative

Atoms have no electric charge, because they maintain an equal number of protons (positively charged subatomic particles) and electrons, subatomic particles with a negative charge. In certain situations, however, the atom may lose or gain one or more electrons and acquire a net charge, becoming an ion.

Aluminum, for instance, has an atomic number of 13, which tells us that an aluminum atom will have 13 protons. Given the fact that every proton has a positive charge, and that most atoms tend to be neutral in charge, this means that there are usually 13 electrons, with a negative charge, present in an atom of aluminum. Yet like all metals, aluminum is capable of forming an ion by losing electrons—in this case, three.

**CATIONS.** Initially, the aluminum atom had a charge of +13 + (–13) = 0; in other words, its charge was neutral due to the equal numbers of protons and electrons. When it becomes an ion, it loses 3 electrons, leaving behind only 10. Now the charge is +13 + (–10) = +3. Thus the remaining aluminum ion is said to have a net positive charge of 3, represented as +3 or 3+. Chemists differ as to whether they represent the plus sign (or the minus sign, in the case of a negatively charged ion) before or after the number. Because both systems of notation are used, these will be applied interchangeably throughout the course of this essay.

When a neutral atom loses one or more electrons, the result is a positively charged ion, or cation (pronounced KAT-ie-un). Cations are usually represented by a superscript number and plus sign: $Al^{+3}$ or $Al^{3+}$, for instance, represents the aluminum cation described above. A cation is named after the element of which it is an ion: thus the ion we have described is either called the aluminum ion, or the aluminum cation.

**ANIONS.** When a neutrally charged atom gains electrons, acquiring a negative charge as a result, this type of ion is known as an anion (AN-ie-un). Anions can be represented symbolically in much the same way as cations: $Cl^-$, for



A common form of field ionization is static electricity. Here, a girl places her hand on a static electricity generator. *(Paul A. Souders/Corbis. Reproduced by permission.)*

instance, is an anion of chlorine that forms when it acquires an electron, thus assuming a net charge of –1. Note that the 1 is not represented in the superscript notation, much as people do not write $10^1$. In both cases, the 1 is assumed, but any number higher than 1 is shown.

The anion described here is never called a chlorine anion; rather, anions have a special nomenclature. If the anion represents, as was the case here, a single element, it is named by adding the suffix -ide to the name of the original element name: chloride. Such is the case, for instance, with a deadly mixture of carbon and nitrogen ($CN^-$), better known as cyanide.

Most often the -ide suffix is used, but in the case of most anions involving more than one element (polyatomic anions), as well as with oxyanions (anions containing oxygen), the rules can get fairly complicated. The general principles for naming anions are as follows:

- -ide: A single element with a negative charge. Note, however, that both hydroxide ($OH^-$) and cyanide ($CN^-$) also receive the -ide suffix, even though they involve more than one element.
- -ate: An oxyanion with the normal number of oxygen atoms, a number that depends on the nature of the compound. Examples include oxalate ($C_2O_4^{-2}$) or chlorate ($ClO_3^-$).
- -ite: An oxyanion containing 1 less oxygen than normal. Examples include chlorite ($ClO_2^-$).
- hypo____ite: An oxyanion with 2 less oxygens than normal, but with the normal charge. An example is hypochlorite, or $ClO^-$.
- per____ate: An oxyanion with 1 more oxygen than normal, but with the normal charge. Perchlorate, or $ClO_4^-$, is an example.
- thio-: An anion in which sulfur has replaced an oxygen. Thus, $SO_4^{-2}$ is called sulfate, whereas $S_2O_3^{-2}$ is called thiosulfate.

## Elements and Ion Charges

As one might expect, given the many differences among families of elements on the periodic table, different elements form ions in different ways. Yet precisely because many of these can be grouped into families, primarily according to the column or group they occupy on the periodic table, it is possible to predict the ways in which they will form ions. The table below provides a few rules of thumb. (All group numbers refer to the North American version of the periodic table;



The damaged reactor at the Chernobyl nuclear plant in the former Soviet Union. The 1986 accident at the plant released ionizing radiation into the atmosphere. *(AP/Wide World Photos. Reproduced by permission.)*

see Periodic Table of Elements essay for an explanation of the differences between this and the IUPAC version.)

- Alkali metals (Group 1) form 1+ cations. For example, the ion of lithium (Li) is always $Li^+$.
- Alkaline earth metals (Group 2) form 2+ cations. Thus, beryllium (Be), for instance, forms a $Be^{2+}$ ion.
- Most Group 3 metals (aluminum, gallium, and indium) form 3+ cations. The cation of aluminum, thus, is designated as $Al_{3+}$.
- Group 6 nonmetals and metalloids (oxygen, sulfur, selenium, and tellurium) form 2– anions. Oxygen, in its normal ionized state, is shown as $O^{2-}$.
- Halogens (Group 7) form 1– anions. Fluorine's anion would therefore be designated as $Fl^-$.

The metals always form positive ions, or cations; indeed, one of the defining characteristics of a metal is that it tends to lose electrons. However, the many elements of the transition metals family form cations with a variety of different charges; for this reason, there is no easy way to classify the ways in which these elements form cations.

Likewise, it should be evident from the above table that nonmetals, such as oxygen or fluorine, gain electrons to form anions. This, too, is a defining characteristic of this broad grouping of elements. The reasons why these elements—both metals and nonmetals—behave as they do are complex, involving the numbers of valence electrons (the electrons involved in chemical bonding) for each group on the periodic table, as well as the octet rule of chemical bonding, whereby elements typically bond so that each atom has eight valence electrons.

## REAL-LIFE APPLICATIONS

### Ionic Bonds, Compounds, and Solids

German chemist Richard Abegg (1869-1910), whose work with noble gases led to the discovery of the octet rule, 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" one another.

As noted, ionic bonds occur when a metal bonds with a nonmetal, and these bonds are extremely strong. Salt, for instance, is formed by an ionic bond between the metal sodium (a +1 cation) and the nonmetal chlorine, a -1 anion. Thus $Na^+$ joins with $Cl^-$ to form NaCl, or table salt. The strength of the bond in salt is reflected by its melting point of 1,472°F (800°C), which is much higher than that of water at 32°F (0°C).

In ionic bonding, two ions start out with different charges and end up forming a bond in which both have eight valence electrons. In a covalent bond, as is formed between nonmetals, two atoms start out as most atoms do, with a net charge of zero. Each ends up possessing eight valence electrons, but neither atom "owns" them; rather, they share electrons. Today, chemists understand that most bonds are neither purely ionic nor purely covalent; rather, there is a wide range of hybrids between the two extremes. The degree to which elements attract one another is a function of electronegativity, or the relative ability of an atom to attract valence electrons.

**IONIC COMPOUNDS AND SOLIDS.** Not only is salt formed by an ionic bond, but it is an ionic compound—that is, a compound containing at least one metal and nonmetal, in which ions are present. Salt is also an example of an ionic solid, or a crystalline solid that contains ions. A crystalline solidis a type of solid in which the constituent parts are arranged in a simple, definite geometric pattern that is repeated in all directions. There are three types of crystalline solid: a molecular solid (for example, sucrose or table sugar), in which the molecules have a neutral electric charge; an atomic solid (a diamond, for instance, which is pure carbon); and an ionic solid.

Salt is not formed of ordinary molecules, in the way that water or carbon dioxide are. (Both of these are molecular compounds, though neither is a solid at room temperature.) The internal structure of salt can be depicted as a repeating series of chloride anions and sodium cations packed closely together like oranges in a crate. Actually, it makes more sense to picture them as cantaloupes and oranges packed together, with the larger chloride anions as the cantaloupes and the smaller sodium cations as the oranges.

If a grocer had to pack these two fruits together in a crate, he would probably put down a layer of cantaloupes, then follow this with a layer of oranges in the spaces between the cantaloupes. This pattern would be repeated as the crate was packed, with the smaller oranges filling the spaces. Much the same is true of the way that chlorine "cantaloupes" and sodium "oranges" are packed together in salt.

This close packing of positive and negative charges helps to form a tight bond, and therefore salt must be heated to a high temperature before it will melt. Solid salt does not conduct electricity, but when melted, it makes for an extremely good conductor. When it is solid, the ions are tightly packed, and thus there is no freedom of movement to carry the electric charge along; but when the structure is disturbed by melting, movement of ions is therefore possible.

## Ionization and Ionization Energy

Water is not a good conductor, although it will certainly allow an electric current to flow through it, which is why it is dangerous to operate an electrical appliance near water. We have already seen that salt becomes a good conductor when melted, but this can also be achieved by dissolving it in water. This is one type of ionization, which can be defined as the process in which one or more electrons are removed from an atom or molecule to create an ion, or the process in which an ionic solid, such as salt, dissociates into its component ions upon being dissolved in a solution.

The amount of energy required to achieve ionization is called ionization energy or ionization potential. When an atom is at its normal energy level, it is said to be in a ground state. At that point, electrons occupy their normal orbital patterns. There is always a high degree of attraction between the electron and the positively charged nucleus, where the protons reside. The energy required to move an electron to a higher orbital pattern increases the overall energy of the atom, which is then said to be in an excited state.

The excited state of the atom is simply a step along the way toward ionizing it by removing the electron. "Step" is an appropriate metaphor, because electrons do not simply drift along a continuum from one energy level to the next, the way a person walks gently up a ramp. Rather,

they make discrete steps, like a person climbing a flight of stairs or a ladder. This is one of the key principles of quantum mechanics, a cutting-edge area of physics that also has numerous applications to chemistry. Just as we speak of a sudden change as a "quantum leap," electrons make quantum jumps from one energy level to another.

Due to the high attraction between the electron and the nucleus, the first electron to be removed is on the outermost orbital—that is, one of the valence electrons. This amount of energy is called the first ionization energy. To remove a second electron will be considerably more difficult, because now the atom is a cation, and the positive charge of the protons in the nucleus is greater than the negative charge of the electrons. Hence the second ionization energy, required to remove a second electron, is much higher than the first ionization energy.

**IONIZATION ENERGIES OF ELEMENTS AND COMPOUNDS.** First and second ionization energy levels for given elements have been established, though it should be noted that hydrogen, because it has only one electron, has only a first ionization energy. In general, the figures for ionization energy increase from left to right along a period or row on the periodic table, and decrease from top to bottom along a column or group.

The reason ionization energy increases along a period is that nonmetals, on the right side of the table, have higher ionization energies than metals, which are on the left side. Ionization energies decrease along a group because elements lower on the table have higher atomic numbers, which means more protons and thus more electrons. It is therefore easier for them to give up one of their electrons than it is for an element with a lower atomic number—just as it would be easier for a millionaire to lose a dollar than it would be for a person earning minimum wage.

For molecules in compounds, the ionization energies are generally related to those of the elements whose atoms make up the molecule. Just as elements with fewer electrons are typically less inclined to give up one, so are molecules with only a few atoms. Thus the ionization energy of carbon dioxide ($CO_2$), with just three atoms, is relatively high. Conversely, in larger molecules as with larger atoms, there are more electrons to give up, and therefore it is easier to separate one of these from the molecules.

**IONIZATION PROCESSES.** A number of methods are used to produce ions for mass spectrometry (discussed below) or other applications. The most common of these methods is electron impact, produced by bombarding a sample of gas with a stream of fast-moving electrons. Though easier than some other methods, this one is not particularly efficient, because it supplies more energy than is needed to remove the electron. An electron gun, usually a heated tungsten wire, produces huge amounts of electrons, which are then fired at the gas. Because electrons are so small, this is rather like using a rapid-fire machine gun to kill mosquitoes: it is almost inevitable that some of the mosquitoes will get hit, but plenty of the rounds will fire into the air without hitting a single insect.

Another ionization process is field ionization, in which ionization is produced by subjecting a molecule to a very intense electric field. Field ionization occurs in daily life, when static electricity builds up on a dry day: the small spark that jumps from the tip of your finger when you touch a doorknob is actually a stream of electrons. In field ionization as applied in laboratories, fine, sharpened wires are used. This process is much more efficient than electron impact ionization, employing far less energy in relation to that required to remove the electrons. Because it deposits less energy into the ion source, the parent ion, it is often used when it is necessary not to damage the ionized specimen.

Chemical ionization employs a method similar to that of electron impact ionization, except that instead of electrons, a beam of positively charged molecular ions is used to bombard and ionize the sample. The ions used in this bombardment are typically small molecules, such as those in methane, propane, or ammonia. Nonetheless, the molecular ion is much larger than an electron, and these collisions are highly reactive, yet they tend to be much more efficient than electron impact ionization. Many mass spectrometers use a source capable of both electron impact and chemical ionization.

Ionization can also be supplied by electromagnetic radiation, with wavelengths shorter than those of visible light—that is, ultraviolet light, x rays, or gamma rays. This process, called photoionization, can ionize small molecules,

such as those of oxygen ($O_2$). Photoionization occurs in the upper atmosphere, where ultraviolet radiation from the Sun causes ionization of oxygen and nitrogen ($N_2$) in their molecular forms.

In addition to these other ionization processes, ionization can be produced in a fairly simple way by subjecting atoms or molecules to the heat from a flame. The temperatures, however, must be several thousand degrees to be effective, and therefore specialized flames, such as an electrical arc, spark, or plasma, are typically used.

**MASS SPECTROMETRY.** As not-ed, a number of the ionization methods described above are used in mass spectrometry, a means of obtaining structure and mass information concerning atoms or molecules. In mass spectrometry, ionized particles are accelerated in a curved path through an electromagnetic field. The field will tend to deflect lighter particles from the curve more easily than heavier ones. By the time the particles reach the detector, which measures the ratio between mass and charge, the ions will have been separated into groups according to their respective mass-to-charge ratios.

When molecules are subjected to mass spectrometry, fragmentation occurs. Each molecule breaks apart in a characteristic fashion, and this makes it possible for a skilled observer to interpret the mass spectrum of the particles generated. Mass spectrometry is used to establish values for ionization energy, as well as to ascertain the mass of substances when that mass is not known. It can also be used to determine the chemical makeup of a substance. Mass spectrometry is applied by chemists, not only in pure research, but in applications within the environmental, pharmaceutical, and forensic (crime-solving) fields. Chemists for petroleum companies use it to analyze hydrocarbons, as do scientists working in areas that require flavor and fragrance analysis.

## Ion Exchange

The process of replacing one ion with another of a similar charge is called ion exchange. When an ionic solution—for example, salt dissolved in water—is placed in contact with a solid containing ions that are only weakly bonded within its crystalline structure, ion exchange is possible. Throughout the exchange, electric neutrality is maintained: in other words, the total number of positive charges in the solid and solution equals the total number of negative charges. The only thing that changes is the type of ion in the solid and in the solution.

There are natural ion exchangers, such as zeolites, a class of minerals that contain aluminum, silicon, oxygen, and a loosely held cation of an alkali metal or alkaline earth metal (Group 1 and Group 2 of the periodic table, respectively). When the zeolite is placed in an ionic solution, exchange occurs between the loosely held zeolite cation and the dissolved cation. In synthetic ion exchangers, used in laboratories, a charged group is attached to a rigid structural framework. One end of the charged group is permanently fixed to the frame, while a positively or negatively charged portion kept loose at the other end attracts other ions in the solution.

**RESINS AND SEMIPERMEABLE MEMBRANES.** Anion resins and cation resins are both solid materials, but in an anion resin, the positive ions are tightly bonded, while the negative ions are loosely bonded. The negative ions will exchange with negative ions in the solution. The reverse is true for a cation resin, in which the negative ions are tightly bonded, while the loosely bonded positive ions exchange with positive ions in the solution. These resins have applications in scientific studies, where they are used to isolate and collect various types of ionic substances. They are also used to purify water, by removing all ions.

Semipermeable membranes are natural or synthetic materials with the ability to selectively permit or retard the passage of charged and uncharged molecules through their surfaces. In the cells of living things, semipermeable membranes regulate the balance between sodium and potassium cations. Kidney dialysis, which removes harmful wastes from the urine of patients with kidneys that do not function properly, is an example of the use of semipermeable membranes to purify large ionic molecules. When seawater is purified by removal of salt, or otherwise unsafe water is freed of its impurities, the water is passed through a semipermeable membrane in a process known as reverse osmosis.

## Ionizing Radiation

We have observed a number of ways in which ionization is useful, and indeed part of nature. But ionizing radiation, which causes ionization

## KEY TERMS

**ANION:** The negatively charged ion that results when an atom gains one or more electrons. An anion (pronounced "AN-ie-un") of a single element is named by adding the suffix -ide to the name of the original element—hence, "chloride." Other rules apply for more complex anions.

**CATION:** The positively charged ion that results when an atom loses one or more electrons. A cation (pronounced KAT-ie-un) is named after the element of which it is an ion and, thus, is called, for instance, the aluminum ion or the aluminum cation.

**CRYSTALLINE SOLID:** A type of solid in which the constituent parts have a simple and definite geometric arrangement that is repeated in all directions. Types of crystalline solids include atomic solids, ionic solids, and molecular solids.

**ELECTRON:** Negatively charged particles in an atom. The number of electrons and protons in an atom is the same, thus canceling out one another. When an atom loses or gains one or more electrons, however—thus becoming an ion—it acquires a net electric charge.

**EXCITED STATE:** A term describing the characteristics of an atom that has acquired excess energy.

**GROUND STATE:** A term describing the characteristics of an atom that is at its ordinary energy level.

**ION:** An atom or group of atoms that has lost or gained one or more electrons, and thus has a net electric charge. There are two types of ions: anions and cations.

**ION EXCHANGE:** The process of replacing one ion with another of similar charge.

**IONIC BONDING:** A form of chemical bonding that results from attractions between ions with opposite electric charges.

**IONIC COMPOUND:** A compound (two or more elements chemically bonded to one another), in which ions are present. Ionic compounds contain at least one metal and nonmetal, joined by an ionic bond.

**IONIC SOLID:** A form of crystalline solid that contains ions. When mixed with a solvent such as water, ions from table salt—an example of an ionic solid—move freely throughout the solution, making it possible to conduct an electric current.

**IONIZATION:** A term that refers to two different processes. In one kind of ionization, one or more electrons are removed from an atom or molecule to create an ion. A second kind of ionization occurs when an ionic solid, such as salt dissociates into its component ions upon being dissolved in a solution.

**IONIZATION ENERGY:** The amount of energy required to achieve ionization in which one or more electrons are removed from an atom or molecule. Another term for this is ionization potential.

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

**ORBITAL:** A pattern of probabilities regarding the position of an electron for an atom in a particular energy state.

**OXYANION:** An anion containing oxygen.

**POLYATOMIC ANION:** An anion involving more than one element.

**PROTON:** A positively charged particle in an atom.

in the substance through which it passes, is extremely harmful. It should be noted that not all radiation is unhealthy: after all, Earth receives heat and light from the Sun by means of radiation. Ionizing radiation, on the other hand, is the kind of radiation associated with radioactive fallout from nuclear warfare, and with nuclear disasters such as the one at Chernobyl in the former Soviet Union in 1986.

Whereas thermal radiation from the Sun can be harmful if one is exposed to it for too long, ionizing radiation is much more so, and involves much greater quantities of energy deposited per area per second. In ionizing radiation, an ionizing particle knocks an electron off an atom or molecule in a living system (that is, human, animal, or plant), freeing an electron. The molecule left behind becomes a free radical, a highly reactive group of atoms with unpaired electrons. These can spawn other free radicals, inducing chemical changes that can cause cancer and genetic damage.

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# MOLECULES

## CONCEPT

Prior to the nineteenth century, chemists pursued science simply by taking measurements, before and after a chemical reaction, of the substances involved. This was an external approach, rather like a person reaching into a box and feeling of the contents without actually being able to see them. With the evolution of atomic theory, chemistry took on much greater definition: for the first time, chemists understood that the materials with which they worked were interacting on a level much too small to see. The effects, of course, could be witnessed, but the activities themselves involved the interactions of atoms in molecules. Just as an atom is the most basic particle of an element, a molecule is the basic particle of a compound. Whereas there are only about 90 elements that occur in nature, many millions of compounds are formed naturally or artificially. Hence the study of the molecule is at least as important to the pursuit of modern chemistry as the study of the atom. Among the most important subjects in chemistry are the ways in which atoms join to form molecules—not just the numbers and types of atoms involved, but the shape that they form together in the molecular structure.

## HOW IT WORKS

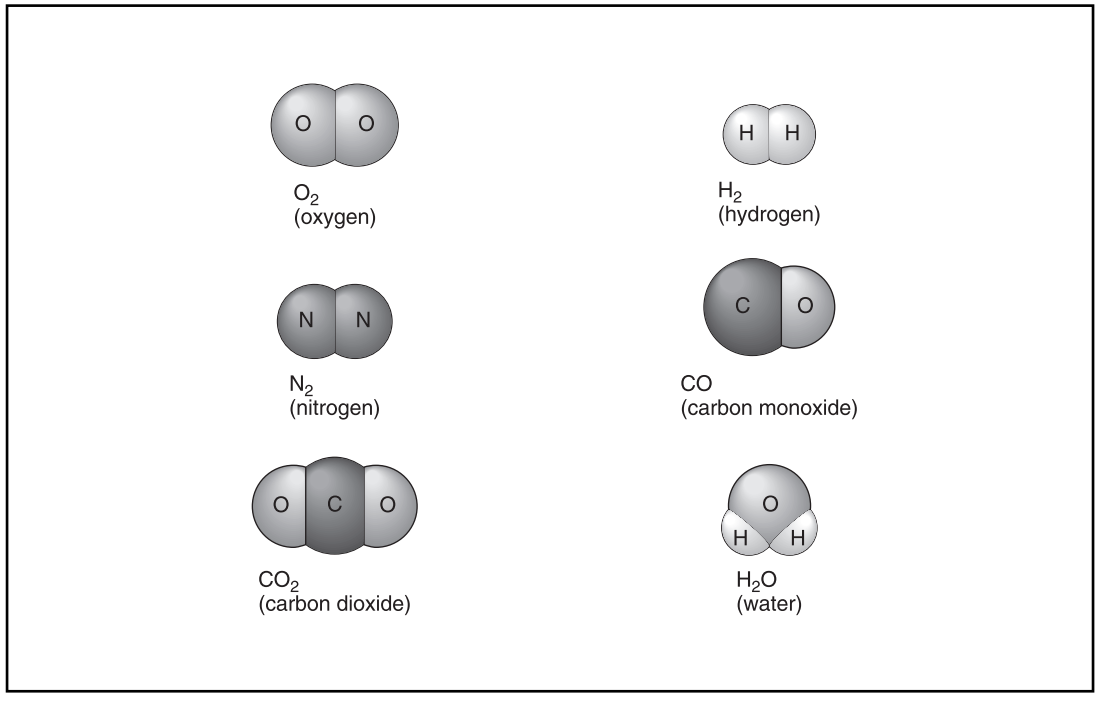
### Introduction to the Molecule

Sucrose or common table sugar, of course, is grainy and sweet, yet it is made of three elements that share none of those characteristics. The formula for sugar is $C_{12}H_{22}O_{11}$, meaning that each molecule is formed by the joining of 12 carbon atoms, 22 hydrogens, and 11 atoms of oxygen. Coal is nothing like sugar—for one thing, it is as black as sugar is white, yet it is almost pure carbon. Carbon, at least, is a solid at room temperature, like sugar. The other two components of sugar, on the other hand, are gases, and highly flammable ones at that.

The question of how elements react to one another, producing compounds that are altogether unlike the constituent parts, is one of the most fascinating aspects of chemistry and, indeed, of science in general. Combined in other ways and in other proportions, the elements in sugar could become water ($H_2O$), carbon dioxide ($CO_2$), or even petroleum, which is formed by the joining of carbon and hydrogen.

Two different compounds of hydrogen and oxygen serve to further illustrate the curiosities involved in the study of molecules. As noted, hydrogen and oxygen are both flammable, yet when they form a molecule of water, they can be used to extinguish most fires. On the other hand, when two hydrogens join with two oxygens to form a molecule of hydrogen peroxide ($H_2O_2$), the resulting compound is quite different from water. In relatively high concentrations, hydrogen peroxide can burn the skin, and in still higher concentrations, it is used as rocket fuel. And whereas water is essential to life, pure hydrogen peroxide is highly toxic.

**THE QUESTION OF MOLECULAR STRUCTURE.** It is not enough, however, to know that a certain combination of atoms forms a certain molecule, because molecules may have identical formulas and yet be quite different substances. In English, for




MODELS OF VARIOUS ELEMENTS.

instance, there is the word "rose." Simply seeing the word, however, does not tell us whether it is a noun, referring to a flower, or a verb, as in "she rose through the ranks." Similarly, the formula of a compound does not necessarily tell what it is, and this can be crucial.

For instance, the formula $C_2H_6O$ identifies two very different substances. One of these is ethyl alcohol, the type of alcohol found in beer and wine. Note that the elements involved are the same as those in sugar, though the proportions are different: in fact, some aspects of the body's reaction to ethyl alcohol are not so different from its response to sugar, since both lead to unhealthy weight gain. In reasonable small quantities, of course, ethyl alcohol is not toxic, or at least only mildly so; yet methyl ether—which has an identical formula—is a toxin.

But the distinction is not simply an external one, as simple as the difference between beer and a substance such as methyl ether, sometimes used as a refrigerant. To put it another way, the external difference reflects an internal disparity: though the formulas for ethyl alcohol and methyl ether are the same, the arrangements of the atoms within the molecules of each are not. The substances are therefore said to be isomers.

In fact $C_2H_6O$ is just one of three types of formula for a compound: an empirical formula, or one that shows the smallest possible whole-number ratio of the atoms involved. By contrast, a molecular formula—a formula that indicates the types and numbers of atoms involved—shows the actual proportions of atoms. If the formula for glucose, a type of sugar ($C_6H_{12}O_6$), were rendered in empirical form, it would be $CH_2O$, which would reveal less about its actual structure. Most revealing of all, however, is a structural formula—a diagram that shows how the atoms are bonded together, complete with lines representing covalent bonds. (Structural formulas such as those that apply the Couper or Lewis systems are discussed in the Chemical Bonding essay, which also examines the subject of covalent bonds.)

Chemists involved in the area of stereochemistry, discussed below, attempt to develop three-dimensional models to show how atoms are arranged in a molecule. Such models for ethyl alcohol and methyl ether, for instance, would reveal that they are quite different, much as the two definitions of rose mentioned above illustrate the two distinctly different meanings. Because stereochemistry is a highly involved and complex subject, it can only be touched upon very briefly in this essay; nonetheless, an under-



TWO HIGH SCHOOL STUDENTS POSE WITH A MODEL OF A DNA MOLECULE. *(James A. Sugar/Corbis. Reproduced by permission.)*

standing of a molecule's actual shape is critical to the work of a professional chemist.

**MOLECULES AND COMPOUNDS.** A molecule can be most properly defined as a group of atoms joined in a specific structure. A compound, on the other hand, is a substance made up of more than one type of atom—in other words, more than one type of element. Not all compounds are composed of discrete molecules, however. For instance, table salt (NaCl) is an ionic compound formed by endlessly repeating clusters of sodium and chlorine that are not, in the strictest sense of the word, molecules.

Salt is an example of a crystalline solid, or a solid in which the constituent parts are arranged in a simple, definite geometric pattern repeated in all directions. There are three kinds of crystalline solids, only one of which has a truly molecular structure. In an ionic solid such as table salt, ions (atoms, or groups of atoms, with an electric charge) bond a metal to a nonmetal—in this case, the metal sodium and the nonmetal chlorine. Another type of crystalline solid, an atomic solid, is formed by atoms of one element bonding to one another. A diamond, made of pure carbon, is an example. Only the third type of crystalline solid is truly molecular in structure: a molecular solid—sugar, for example—is one in which the molecules have a neutral electric charge.

Not all solids are crystalline; nor, of course, are all compounds solids: water, obviously, is a liquid at room temperature, while carbon dioxide is a gas. Nor is every molecule composed of more than one element. Oxygen, for instance, is ordinarily diatomic, meaning that even in its elemental form, it is composed of two atoms that join in an $O_2$ molecule. It is obvious, then, that the defining of molecules is more complex than it seems. One can safely say, however, that the vast majority of compounds are made up of molecules in which atoms are arranged in a definite structure.

In the essay that follows, we will discuss the ways atoms join to form molecules, a subject explored in more depth within the Chemical Bonding essay. (In addition, compounds themselves are examined in somewhat more detail within the Compounds essay.) We will also briefly examine how molecules bond to other molecules in the formation of solids and liquids. First, however, a little history is in order: as noted in the introduction to this essay, chemists did not always possess a clear understanding of the nature of a molecule.

### A Brief History of the Molecule

In ancient and medieval times, early chemists—some of whom subscribed to an unscientific system known as alchemy—believed that one element could be transformed into another. Thus many an alchemist devoted an entire career to the vain pursuit of turning lead into gold. The alchemists were at least partially right, however: though one element cannot be transformed into another (except by nuclear fusion), it is possible to change the nature of a compound by altering the relations of the elements within it.

Modern understanding of the elements began to emerge in the seventeenth century, but the true turning point came late in the eighteenth century. It was then that French chemist Antoine Lavoisier (1743-1794) defined an element as a simple substance that could not be separated into simpler substances by chemical means. Around the same time, another French chemist, Joseph-Louis Proust (1754-1826) stated that a given compound always contained the same proportions of mass between elements. The ideas of Lavoisier and Proust were revolutionary at the time, and these concepts pointed to a substructure, invisible to the naked eye, underlying all matter.

In 1803, English chemist John Dalton (1766-1844) defined that substructure by introducing the idea that the material world is composed of tiny particles called atoms. Despite the enormous leap forward that his work afforded to chemists, Dalton failed to recognize that matter is not made simply of atoms. Water, for instance, is not just a collection of "water atoms": clearly, there is some sort of intermediary structure in which atoms are combined. This is the molecule, a concept introduced by Italian physicist Amedeo Avogadro (1776-1856).

**Avogadro and the idea of the molecule.** French chemist and physicist Joseph Gay-Lussac (1778-1850) had announced in 1809 that gases combine to form compounds in simple proportions by volume. As Gay-Lussac explained, the ratio, by weight, between hydrogen and oxygen in water is eight to one. The fact that this ratio was so "clean," involving whole numbers rather than decimals, intrigued Avogadro, who in 1811 proposed that equal volumes of gases have the same number of particles if measured at the same temperature and pressure. This, in turn, led him to the hypothesis that water is not composed simply of atoms, but of molecules in which hydrogen and oxygen combine.

For several decades, however, chemists largely ignored Avogadro's idea of the molecule. Only in 1860, four years after his death, was the concept resurrected by Italian chemist Stanislao Cannizzaro (1826-1910). Of course, the understanding of the molecule has progressed enormously in the years since then, and much of this progress is an outcome of advances in the study of subatomic structure. Only in the early twentieth century did physicists finally identify the electron, the negatively charged subatomic particle critical to the bonding of atoms.

## Real-Life Applications

### Molecular Mass

Just as the atoms of elements have a definite mass, so do molecules—a mass equal to that of the combined atoms in the molecule. The figures for the atomic mass of all elements are established, and can be found on the periodic table; therefore, when one knows the mass of a hydrogen atom and an oxygen atom, as well as the fact that there are two hydrogens and one oxygen in a molecule of water, it is easy to calculate the mass of a water molecule.

Individual molecules cannot easily be studied; therefore, the mass of molecules is compared by use of a unit known as the mole. The mole contains $6.022137 \times 10^{23}$ molecules, a figure known as Avogadro's number, in honor of the man who introduced the concept of the molecule. When necessary, it is possible today to study individual molecules, or even atoms and subatomic particles, using techniques such as mass spectrometry.

### Bonding Within Molecules

Note that the mass of an atom in a molecule does not change; nor, indeed, do the identities of the individual atoms. An oxygen atom in water is the same oxygen atom in sugar, or in any number of other compounds. With regard to compounds, it should be noted that these are not the same thing as a mixture, or a solution. Sugar or salt can be dissolved in water at the appropriate tempera-

tures, but the resulting solution is not a compound; the substances are joined physically, but they are not chemically bonded.

Chemical bonding is the joining, through electromagnetic force, of atoms representing different elements. Each atom possesses a certain valency, which determines its ability to bond with atoms of other elements. Valency, in turn, is governed by the configuration of valence electrons at the highest energy level (the shell) of the atom.

While studying noble gases, noted for their tendency not to bond, German chemist Richard Abegg (1869-1910) discovered that these gases always have eight valence electrons. This led to the formation of the octet rule: most elements (with the exception of hydrogen and a few others) are inclined to bond in such a way that they end up with eight valence electrons.

When a metal bonds to a nonmetal, this is known as ionic bonding, which results from attractions between ions with opposite electric charges. In ionic bonding, two ions start out with different charges and form a bond in which both have eight valence electrons. Nonmetals, however, tend to form covalent bonds. In a covalent bond, two atoms start out as most atoms do, with a net charge of zero. Each ends up possessing eight valence electrons, but neither atom "owns" them; rather, they share electrons.

**ELECTRONEGATIVITY.** Not all elements bond covalently in the same way. Each has a certain value of electronegativity—the relative ability of an atom to attract valence electrons. Elements capable of bonding are assigned an electronegativity value ranging from a minimum of 0.7 for cesium to a maximum of 4.0 for fluorine. The greater the electronegativity value, the greater the tendency of an element to attract valence electrons.

When substances of differing electronegativity values form a covalent bond, this is described as polar covalent bonding. Water is an example of a molecule with a polar covalent bond. Because oxygen has a much higher electronegativity (3.5) than hydrogen (2.1), the electrons tend to gravitate toward the oxygen atom. By contrast, molecules of petroleum, a combination of carbon and hydrogen, tend to be nonpolar, because carbon (2.5) and hydrogen have very similar electronegativity values.

A knowledge of electronegativity values can be used to make predictions concerning bond polarities. Bonds that involve atoms whose electronegativities differ by more than 2 units are substantially ionic, whereas bonds between atoms whose electronegativities differ by less than 2 units are polar covalent. If the atoms have the same or similar electronegativity values, the bond is covalent.

## Attractions Between Molecules

The energy required to pull apart a molecule is known as bond energy. Covalent bonds that involve hydrogen are among the weakest bonds between atoms, and hence it is relatively easy to separate water into its constituent parts, hydrogen and oxygen. (This is sometimes done by electrolysis, which involves the use of an electric current to disperse atoms.) Double and triple covalent bonds are stronger, but strongest of all is an ionic bond. The strength of the bond energy in salt, for instance, is reflected by its melting point of 1,472°F (800°C), much higher than that of water, at 32°F (0°C).

Bond energy relates to the attraction between atoms in a molecule, but in considering various substances, it is also important to recognize the varieties of bonds between molecules—that is, intermolecular bonding. For example, the polar quality of a water molecule gives it a great attraction for ions, and thus ionic substances such as salt and any number of minerals dissolve easily in water. On the other hand, we have seen that petroleum is essentially nonpolar, and therefore, an oil molecule offers no electric charge to bond it with a water molecule. For this reason, oil and water do not mix.

The bonding between water molecules is known as a dipole-dipole attraction. This type of intermolecular bond can be fairly strong in the liquid or solid state, though it is only about 1% as strong as a covalent bond within a molecule. When a substance containing molecules joined by dipole-dipole attraction is heated to become a gas, the molecules spread far apart, and these bonds become very weak. On the other hand, when hydrogen bonds to an atom with a high value of electronegativity (fluorine, for example), the dipole-dipole attraction between these molecules is particularly strong. This is known as hydrogen bonding.

## KEY TERMS

**AVOGADRO'S NUMBER:** A figure, named after Italian physicist Amedeo Avogadro (1776-1856), equal to 6.022137 x $10^{23}$. Avogadro's number indicates the number of molecules in a mole.

**BOND ENERGY:** The energy required to pull apart the atoms in a chemical bond.

**CHEMICAL BONDING:** The joining, through electromagnetic force, of atoms representing different elements.

**COMPOUND:** A substance made up of atoms of more than one element. These atoms are usually joined in molecules.

**COVALENT BONDING:** A type of chemical bonding in which two atoms share valence electrons.

**DIATOMIC:** A term describing an element that exists as molecules composed of two atoms.

**DIPOLE-DIPOLE ATTRACTION:** A form of intermolecular bonding between molecules formed by a polar covalent bond.

**ELECTRON:** A negatively charged particle in an atom.

**ELECTRONEGATIVITY:** The relative ability of an atom to attract valence electrons.

**EMPIRICAL FORMULA:** A chemical formula that shows the smallest possible whole-number ratio of the atoms involved. Compare with molecular formula and structural formula.

**HYDROGEN BONDING:** A kind of dipole-dipole attraction between molecules formed of hydrogen along with an element having a high electronegativity.

**INTERMOLECULAR BONDING:** The bonding that exists between molecules. This is not to be confused with chemical bonding, the bonding of atoms within a molecule.

**ION:** An atom or group of atoms that has lost or gained one or more electrons, and thus has a net electric charge.

**IONIC BONDING:** A form of chemical bonding resulting from attractions between ions with opposite electric charges.

**ISOMERS:** Substances having the same chemical formula, but which are chemically dissimilar due to differences in the arrangement of atoms.

**LONDON DISPERSION FORCES:** A term describing the weak intermolecular bond between molecules that are not formed by a polar covalent bond.

Even a nonpolar molecule, however, must have some attraction to other nonpolar molecules. The same is true of helium and the other noble gases, which are highly nonattractive but can be turned into liquids or even solids at extremely low temperatures. The type of intermolecular attraction that exists in such a situation is described by the term London dispersion forces. The name has nothing to do with the capital of England: it is a reference to German-American physicist Fritz Wolfgang London (1900-1954), who in the 1920s studied the molecule from the standpoint of quantum mechanics.

Because electrons are not uniformly distributed around the nucleus of an atom at every possible moment, instantaneous dipoles are formed when most of the electrons happen to be on one side of an atom. Of course, this only happens for an infinitesimal fraction of time, but it serves to create a weak attraction. Only at very low tem-

## KEY TERMS CONTINUED

**MOLE:** The SI fundamental unit for "amount of substance." A mole is, generally speaking, Avogadro's number of molecules; however, in the more precise SI definition, a mole is equal to the number of carbon atoms in 12.01 g of carbon.

**MOLECULAR FORMULA:** A chemical formula that indicates the types and numbers of atoms involved, showing the actual proportions of atoms in a molecule. Compare with empirical formula and structural formula.

**MOLECULAR SOLID:** A form of crystalline solid—a solid in which the constituent parts have a simple and definite geometric arrangement repeated in all directions—in which the molecules have a neutral electric charge. Table sugar (sucrose) is an example.

**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.

**OCTET RULE:** A term describing the distribution of valence electrons that takes place in chemical bonding for most elements, which end up with eight valence electrons.

**POLAR COVALENT BONDING:** The type of chemical bonding between atoms that have differing values of electronegativity. Water molecules are an example of a polar covalent bond.

**SHELL:** The orbital pattern of the valence electrons at the outside of an atom.

**STEREOCHEMISTRY:** The area of chemistry devoted to the three-dimensional arrangement of atoms in a molecule.

**STRUCTURAL FORMULA:** A diagram that shows how the atoms are bonded together, complete with lines representing covalent bonds. Compare with empirical formula and molecular formula.

**VALENCE ELECTRONS:** Electrons that occupy the highest energy levels in an atom. These are the only electrons involved in chemical bonding.

**VALENCY:** The property of the atom of one element that determines its ability to bond with atoms of other elements.

**VSEPR (VALENCE SHELL ELECTRON PAIR REPULSION) MODEL:** A means of representing the three-dimensional structure of atoms in a molecule.

peratures do London dispersion forces become strong enough to result in the formation of a solid. (Thus, for instance, oil and rubbing alcohol freeze only at low temperatures.)

### Molecular Structure

The Couper system and Lewis structures, discussed in the Chemical Bonding essay, provide a means of representing the atoms that make up a molecule. Though Lewis structures show the distribution of valence electrons, they do not represent the three-dimensional structure of the molecule. As noted earlier in this essay, the structure is highly important, because two compounds may be isomers, meaning that they have the same proportions of the same elements, yet are different substances.

Stereochemistry is the realm of chemistry devoted to the three-dimensional arrangement of atoms in a molecule. One of the most impor-

tant methods used is known as the VSEPR model (valence shell electron pair repulsion). In bonding, elements always share at least one pair of electrons, and the VSEPR model begins with the assumption that the electron pairs must be as far apart as possible to minimize their repulsion, since like charges repel.

VSEPR structures can be very complex, and the rules governing them will not be discussed here, but a few examples can be given. If there are just two electron pairs in a bond between three atoms, the structure of a VSEPR model is like that of a stick speared through a ball, with two other balls attached at each end. The "ball" is an atom, and the "stick" represents the electron pairs. In water, there are four electron pairs, but still only three atoms and two bonds. In order to keep the electron pairs as far apart as possible, the angle between the two hydrogen atoms attached to the oxygen is 109.5°.

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# ELEMENTS

ELEMENTS
PERIODIC TABLE OF ELEMENTS
FAMILIES OF ELEMENTS

# ELEMENTS

## CONCEPT

The elements are at the heart of chemistry, and indeed they are at the heart of life as well. Every physical substance encountered in daily life is either an element, or more likely a compound containing more than one element. There are millions of compounds, but only about 100 elements, of which only 88 occur naturally on Earth. How can such vast complexity be created from such a small amount of elements? Consider the English alphabet, with just 26 letters, with which an almost infinite number of things can be said or written. Even more is possible with the elements, which greatly outnumber the letters of the alphabet. Despite the relatively great quantity of elements, however, just two make up almost the entire mass of the universe—and these two are far from abundant on Earth. A very small number of elements, in fact, are essential to life on this planet, and to the existence of human beings.

## HOW IT WORKS

### The Focal Point of Chemistry

Like physics, chemistry is concerned with basic, underlying processes that explain how the universe works. Indeed, these two sciences, along with astronomy and a few specialized fields, are the only ones that address phenomena both on the Earth and in the universe as a whole. By contrast, unless or until life on another planet is discovered, biology has little concern with existence beyond Earth's atmosphere, except inasmuch as the processes and properties in outer space affect astronauts.

While physics and chemistry address many of the same fundamental issues, they do so in very different ways. To make a gross generalization—subject to numerous exceptions, but nonetheless useful in clarifying the basic difference between the two sciences—physicists are concerned with external phenomena, and chemists with internal ones.

For instance, when physicists and chemists study the interactions between atoms, unless physicists focus on some specialized area of atomic research, they tend to treat all atoms as more or less the same. Chemists, on the other hand, can never treat atoms as though they are just undifferentiated particles colliding in space. The difference in structure between one kind of atom and another, in fact, is the starting-point of chemical study.

### Structure of the Atom

An atom is the fundamental particle in a chemical element, or a substance that cannot be broken down into another substance by chemical means. Clustered at the center, or nucleus, of the atom are protons, which have a positive electric charge, and neutrons, which possess no charge.

Spinning around the nucleus are electrons, which are negatively charged. The vast majority of the atom's mass is made up by the protons and neutrons, which have approximately the same mass, whereas that of the electron is much smaller. The mass of an electron is about 1/1836 that of proton, and 1/1839 that of a neutron.

It should be noted that the nucleus, though it constitutes most of the atom's mass, is only a tiny portion of the atom's volume. If the nucleus were the size of a grape, in fact, the electrons would, on average, be located about a mile away.

| Element | Symbol | Percent of all atoms* | | | | Characteristics under ordinary room conditions |
|---|---|---|---|---|---|---|
| | | In the universe | In the earth's crust | In sea water | In the human body | |
| Aluminum | Al | — | 6.3 | — | — | A lightweight, silvery metal |
| Calcium | Ca | — | 2.1 | — | 0.2 | Common in minerals, seashells, and bones |
| Carbon | C | — | — | — | 10.7 | Basic in all living things |
| Chlorine | Cl | — | — | 0.3 | — | A toxic gas |
| Copper | Cu | — | — | — | — | The only red metal |
| Gold | Au | — | — | — | — | The only yellow metal |
| Helium | He | 7.1 | — | — | — | A very light gas |
| Hydrogen | H | 92.8 | 2.9 | 66.2 | 60.6 | The lightest of all elements; a gas |
| Iodine | I | — | — | — | — | A nonmetal; used as antiseptic |
| Iron | Fe | — | 2.1 | — | — | A magnetic metal; used in steel |
| Lead | Pb | — | — | — | — | A soft, heavy metal |
| Magnesium | Mg | — | 2.0 | — | — | A very light metal |
| Mercury | Hg | — | — | — | — | A liquid metal; one of the two liquid elements |
| Nickel | Ni | — | — | — | — | A noncorroding metal; used in coins |
| Nitrogen | N | — | — | — | 2.4 | A gas; the major component of air |
| Oxygen | O | — | 60.1 | 33.1 | 25.7 | A gas; the second major component of air |
| Phosphorus | P | — | — | — | 0.1 | A nonmetal; essential to plants |
| Potassium | K | — | 1.1 | — | — | A metal; essential to plants; commonly called "potash" |
| Silicon | Si | — | 20.8 | — | — | A semiconductor; used in electronics |
| Silver | Ag | — | — | — | — | A very shiny, valuable metal |
| Sodium | Na | — | 2.2 | 0.3 | — | A soft metal; reacts readily with water, air |
| Sulfur | S | — | — | — | 0.1 | A yellow nonmetal; flammable |
| Titanium | Ti | — | 0.3 | — | — | A light, strong, noncorroding metal used in space vehicles |
| Uranium | U | — | — | — | — | A very heavy metal; fuel for nuclear power |

*If no number is entered, the element constitutes less than 0.1 percent.

THE MOST COMMON AND/OR IMPORTANT CHEMICAL ELEMENTS.

## ISOTOPES

Atoms of the same element always have the same number of protons, and since this figure is unique for a given element, each element is assigned an atomic number equal to the number of protons in its nucleus. Two atoms may have the same number of protons, and thus be of the same element, yet differ in their number of neutrons. Such atoms are called isotopes.

Isotopes are generally represented as follows: ${}^{m}_{a}S$, where *S* is the symbol of the element, *a* is the atomic number, and *m* is the mass number—the sum of protons and neutrons in the atom's nucleus. For the stable silver isotope designated as ${}^{93}_{47}Ag$, for instance, Ag is the element symbol (discussed below); 47 its atomic number; and 93 the mass number. From this, it is easy to discern that this particular stable isotope has 46 neutrons in its nucleus.

Because the atomic number of any element is established, sometimes isotopes are represented simply with the mass number thus: $^{93}Ag$. They may also be designated with a subscript notation indicating the number of neutrons, so that one can obtain this information at a glance without having to do the arithmetic. For the silver isotope shown here, this is written as ${}^{93}_{47}Ag_{46}$. Isotopes are sometimes indicated by simple nomenclature as well: for instance, carbon-12 or carbon-13.

### Ions

The number of electrons in an atom is usually the same as the number of protons, and thus most atoms have a neutral charge. In certain situations, however, the atom may lose or gain one or more electrons and acquire a net charge, becoming an ion. The electrons are not "lost" when an atom becomes an ion: they simply go elsewhere.

Aluminum (Al), for instance, has an atomic number of 13, which tells us that an aluminum atom will have 13 protons. Given the fact that every proton has a positive charge, and that most atoms tend to be neutral in charge, this means that there are usually 13 electrons, with a negative charge, present in an atom of aluminum. Aluminum may, however, form an ion by losing three electrons.

**CATIONS.** After its three electrons have departed, the remaining aluminum ion has a net positive charge of 3, represented as +3. How do we know this? Initially the atom had a charge of +13 + (–13) = 0. With the exit of the 3 electrons, leaving behind only 10, the picture changes: now the charge is +13 + (–10) = +3.

When a neutral atom loses one or more electrons, the result is a positively charged ion, or cation (pronounced KAT-ie-un). Cations are represented by a superscript number and plus sign after the element symbol: $Al^{3+}$, for instance, represents the aluminum cation described above. (Some chemists represent this with the plus sign before the number—for example, $Al^{+3}$.) A cation is named after the element of which it is an ion: thus the ion we have described is called either the aluminum ion, or the aluminum cation.

**ANIONS.** When a neutrally charged atom gains electrons, and as a result acquires a negative charge, this type of ion is known as an anion (AN-ie-un). Anions can be represented symbolically in much the same way of cations: C1-, for instance, is an anion of chlorine that forms when it acquires an electron, thus assuming a net charge of –1. Note that the 1 is not represented in the superscript notation, much as people do not write $10^1$. In both cases, the 1 is assumed, whereas any number higher than 1 is shown.

The anion described here is never called a chlorine anion; rather, anions have a special nomenclature. If the anion represents, as is the case here, a single element, it is named by adding the suffix -ide to the name of the original element name: hence it would be called chloride. Other anions involve more than one element, and in these cases other rules apply for designating names. A few two-element anions use the -ide ending; such is the case, for instance, with a deadly mixture of carbon and nitrogen ($CN^-$), better known as cyanide.

For anions involving oxygen, there may be different prefixes and suffixes, depending on the relative number of oxygen atoms in the anion.

## REAL-LIFE APPLICATIONS

### The Periodic Table

Note that an ion is never formed by a change in the number of protons: that number, as noted earlier, is a defining characteristic of an element. If all we know about a particular atom is that it has one proton, we can be certain that it is an atom of hydrogen. Likewise, if an atom has 79 protons, it is gold.

Knowing these quantities is not a matter of memorization: rather, one can learn this and much more by consulting the periodic table of elements. The periodic table is a chart, present in virtually every chemistry classroom in the world,

showing the elements arranged in order of atomic number. Elements are represented by boxes containing the atomic number, element symbol, and average atomic mass, in atomic mass units, for that particular element. Vertical columns within the periodic table indicate groups or "families" of elements with similar chemical characteristics.

These groups include alkali metals, alkaline earth metals, halogens, and noble gases. In the middle of the periodic table is a wide range of vertical columns representing the transition metals, and at the bottom of the table, separated from it, are two other rows for the lanthanides and actinides.

## An Overview of the Elements

As of 2001, there 112 elements, of which 88 occur naturally on Earth. (Some sources show 92 naturally occurring elements; however, a few of the elements with atomic numbers below 92 have not actually been found in nature.) The others were created synthetically, usually in a laboratory, and because these are highly radioactive, they exist only for fractions of a second. The number of elements thus continues to grow, but these "new" elements have little to do with the daily lives of ordinary people. Indeed, this is true even for some of the naturally occurring elements: few people who are not chemically trained, for instance, are able to identify thulium, which has an atomic number of 69.

Though an element can theoretically exist as a gas, liquid, or a solid, in fact the vast majority of elements are solids. Only 11 elements—the six noble gases, along with hydrogen, nitrogen, oxygen, fluorine, and chlorine—exist in the gaseous state at a normal temperature of about 77°F (25°C). Just two are liquids at normal temperature: mercury, a metal, and the non-metal bromine. (The metal gallium becomes liquid at just 85.6°F, or 29.76°C.) The rest are all solids.

The noble gases are monatomic, meaning that they exist purely as single atoms. So too are the "noble metals," such as gold, silver, and platinum. "Noble" in this context means "set apart": noble gases and noble metals are known for their tendency not to react to, and hence not to bond with, other elements. On the other hand, a number of other elements are described as diatomic, meaning that two atoms join to form a molecule.

## Names of the Elements

**element symbol.** As noted above, the periodic table includes the element symbol or chemical symbol—a one-or two-letter abbreviation for the name of the element. Many of these are simple one-letter designations: O for oxygen, or C for carbon. Others are two-letter abbreviations, such as Ne for neon or Si for silicon. Note that the first letter is always capitalized, and the second is always lowercase.

In many cases, the two-letter symbols indicate the first and second letters of the element's name, but this is far from universal. Cadmium, for example, is abbreviated Cd, while platinum is Pt. In other cases, the symbol seems to have nothing to do with the element name as it is normally used: for instance, Au for gold or Fe for iron.

Many of the one-letter symbols indicate elements discovered early in history. For instance, carbon is represented by C, and later "C" elements took two-letter designations: Ce for cerium, Cr for chromium, and so on. But many of those elements with apparently strange symbols were among the first discovered, and this is precisely why the symbols make little sense to a person who does not recognize the historical origins of the name.

**historical background on some element names.** For many years, Latin was the language of communication between scientists from different nations; hence the use of Latin names such as *aurum* ("shining dawn") for gold, or *ferrum,* the Latin word for iron. Likewise, lead (Pb) and sodium (Na) are designated by their Latin names, *plumbum* and *natrium,* respectively.

Some chemical elements are named for Greek or German words describing properties of the element—for example, bromine (Br), which comes from a Greek word meaning "stench." The name of cobalt comes from a German term meaning "underground gnome," because miners considered the metal a troublemaker. The names of several elements with high atomic numbers reflect the places where they were originally discovered or created: francium, germanium, americium, californium.

Americium and californium, with atomic numbers of 95 and 98 respectively, are among those elements that do not occur naturally, but

were created artificially. The same is true of several elements named after scientists—among them einsteinium, after Albert Einstein (1879-1955), and nobelium after Alfred Nobel (1833-1896), the Swedish inventor of dynamite who established the Nobel Prize.

## ABUNDANCE OF ELEMENTS

**IN THE UNIVERSE.** The first two elements on the periodic table, hydrogen and helium, represent 99.9% of the matter in the entire universe. This may seem astounding, but Earth is a tiny dot within the vastness of space, and hydrogen and helium are the principal elements in stars.

All elements, except for those created artificially, exist both on Earth and throughout the universe. Yet the distribution of elements on Earth is very, very different from that in other places—as well it should be, given the fact that Earth is the only planet known to support life. Hydrogen, for instance, constitutes only about 0.87%, by mass, of the elements found in the planet's crust, waters, and atmosphere. As for helium, it is not even among the 18 most abundant elements on Earth.

**ON EARTH.** That great element essential to animal life, 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-quarters of the elemental mass of Earth. Add in aluminum (7.5%), iron (4.71%), calcium (3.39%), sodium (2.63%), potassium (2.4%), and magnesium (1.93%), and these eight elements make up about 97.46% of Earth's material.

In addition to hydrogen, whose distribution is given above, 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 elements.



THIS WOMAN'S GOITER IS PROBABLY THE RESULT OF A LACK OF IODINE IN HER DIET. *(Lester V. Bergman/Corbis. Reproduced by permission.)*

## ELEMENTS IN THE HUMAN BODY

Fans of science-fiction are familiar with the phrase "carbon-based life form," which is used, for instance, by aliens in sci-fi movies to describe humans. In fact, the term is a virtual redundancy on Earth, since all living things contain carbon.

Essential though it is to life, carbon as a component of the human body takes second place to oxygen, which is an even larger proportion of the body's mass—65.0%—than it is of the Earth. Carbon accounts for 18%, and hydrogen for 10%, meaning that these three elements make up 93% of the body's mass. Most of the remainder is taken up by 10 other elements: 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%).

**TRACE ELEMENTS.** As small as the amount of zinc is in the human body, there are still other elements found in even smaller quantities. These are known as trace elements, because only traces of them are present in the body. Yet they are essential to human well-being: without enough iodine, for instance, a person can devel-

## KEY TERMS

**ANION:** The negative ion that results when an atom gains one or more electrons. An anion (pronounced "AN-ie-un") of an element is never called, for instance, the chlorine anion. Rather, for an anion involving a single element, it is named by adding the suffix -ide to the name of the original element—hence, "chloride." Other rules apply for more complex anions.

**ATOM:** The smallest particle of an element. An atom can exist either alone or in combination with other atoms in a molecule. Atoms are made up of protons, neutrons, and electrons. An atom that loses or gains one or more electrons, and thus has a net charge, is an ion. Atoms that have the same number of protons—that is, are of the same element—but differ in number of neutrons are known as isotopes.

**ATOMIC MASS UNIT:** An SI unit (abbreviated amu), equal to $1.66 \cdot 10^{-24}$ 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. If a substance is a compound, the average atomic mass of all atoms in a molecule of that substance must be added together to yield the average molecular mass of that substance.

**CATION:** The positive ion that results when an atom loses one or more electrons. A cation (pronounced KAT-ie-un) is named after the element of which it is an ion and thus is called, for instance, the aluminum ion or the aluminum cation.

**CHEMICAL SYMBOL:** Another term for element symbol.

**COMPOUND:** A substance made up of atoms of more than one element. These atoms are usually joined in molecules.

**DIATOMIC:** A term describing an element that exists as molecules composed of two atoms. This is in contrast to monatomic elements.

**ELECTRON:** Negatively charged particles in an atom. Electrons, which spin around the protons and neutrons that make up the atom's nucleus, constitute a very small portion of the atom's mass. The number of electrons and protons is the same, thus canceling out one another. But when an atom loses or gains one or more electrons, however—thus becoming an ion—it acquires a net electric charge.

op a goiter, a large swelling in the neck area. Chromium helps the body metabolize sugars, which is why people concerned with losing weight and/or toning their bodies through exercise may take a chromium supplement.

Even arsenic, lethal in large quantities, is a trace element in the human body, and medicines for treating illnesses such as the infection known as "sleeping sickness" contain tiny amounts of arsenic. Other trace elements include cobalt, copper, fluorine, manganese, molybdenum, nickel, selenium, silicon, and vanadium.

**MAINTAINING AND IMPROVING HEALTH.** Though these elements are present in trace quantities within the human body, that does not mean that exposure to large amounts of them is healthy. Arsenic, of course, is a good example; so too is aluminum. Aluminum is present in unexpected places: in baked goods, for instance, where a compound containing alu-

## KEY TERMS CONTINUED

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

**ELEMENT SYMBOL:** A one- or two-letter abbreviation for the name of an element. These may be a single capitalized letter (O for oxygen), or a capitalized letter followed by a lowercase one (Ne for neon). Sometimes the second letter is not the second letter of the element name (for example, Pt for platinum). In addition, the symbol may refer to an original Greek or Latin name, rather than the name used now, is the case with Au (aurum) for gold.

**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.

**MASS NUMBER:** The sum of protons and neutrons in an atom's nucleus. Where an isotope is represented, the mass number is placed above the atomic number to the left of the element symbol.

**MOLECULE:** A group of atoms, usu-ally but not always representing more than one element, joined in a structure. Compounds are typically made of up molecules.

**MONATOMIC:** A term describing an element that exists as single atoms. This in contrast to diatomic elements.

**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.

**PERIODIC TABLE OF ELEMENTS:** A chart that shows the elements arranged in order of atomic number, along with element symbol and the average atomic mass (in atomic mass units) for that particular element. Vertical columns within the periodic table indicate groups or "families" of elements with similar chemical characteristics.

**PROTON:** A positively charged particle in an atom. Protons and neutrons, which together form the nucleus around which electrons spin, have approximately the same mass—a mass that is many times greater than that of an electron. The number of protons in the nucleus of an atom is the atomic number of an element.

minum (baking powder) is sometimes used in the leavening process; or even in cheeses, as an aid to melting when heated. The relatively high concentrations of aluminum in these products, as well as fluorine in drinking water, has raised concerns among some scientists.

Generally speaking, an element is healthy for the human body in proportion to its presence in the body. With trace elements and others that are found in smaller quantities, however, it is sometimes possible and even advisable to increase the presence of those elements by taking dietary supplements. Hence a typical multivitamin contains calcium, iron, iodine, magnesium, zinc, selenium, copper, chromium, manganese, molybdenum, boron, and vanadium.

For most of these, recommended daily allowances (RDA) have been established by the federal government. Usually, people do not take

sodium as a supplement, though—Americans already get more than their RDA of sodium through salt, which is overly abundant in the American diet.

## WHERE TO LEARN MORE


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# PERIODIC TABLE OF ELEMENTS

## CONCEPT

In virtually every chemistry classroom on the planet, there is a chart known as the periodic table of elements. At first glance, it looks like a mere series of boxes, with letters and numbers in them, arranged according to some kind of code not immediately clear to the observer. The boxes would form a rectangle, 18 across and 7 deep, but there are gaps in the rectangle, particularly along the top. To further complicate matters, two rows of boxes are shown along the bottom, separated from one another and from the rest of the table. Even when one begins to appreciate all the information contained in these boxes, the periodic table might appear to be a mere chart, rather than what it really is: one of the most sophisticated and usable means ever designed for representing complex interactions between the building blocks of matter.

## HOW IT WORKS

### Introduction to the Periodic Table

As a testament to its durability, the periodic table—created in 1869—is still in use today. Along the way, it has incorporated modifications involving subatomic properties unknown to the man who designed it, Russian chemist Dmitri Ivanovitch Mendeleev (1834-1907). Yet Mendeleev's original model, which we will discuss shortly, was essentially sound, inasmuch as it was based on the knowledge available to chemists at the time.

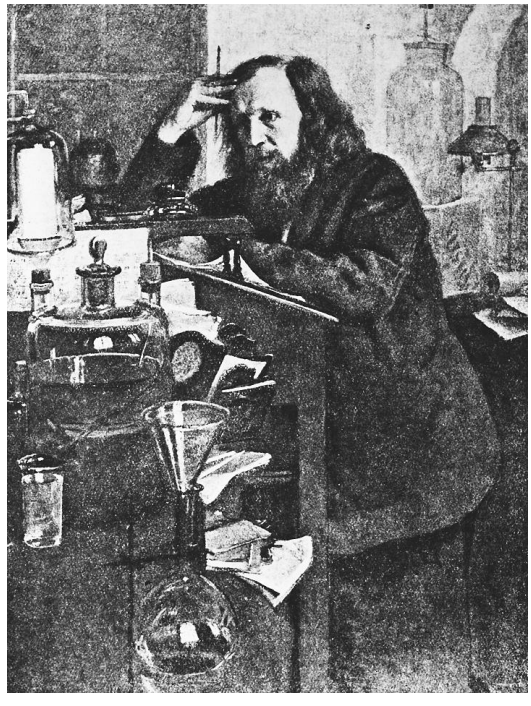
In 1869, the electromagnetic force fundamental to chemical interactions had only recently been identified; the modern idea of the atom was less than 70 years old; and another three decades were to elapse before scientists began uncovering the substructure of atoms that causes them to behave as they do. Despite these limitations in the knowledge available to Mendeleev, his original table was sound enough that it has never had to be discarded, but merely clarified and modified, in the years since he developed it.

The rows of the periodic table of elements are called periods, and the columns are known as groups. Each box in the table represents an element by its chemical symbol, along with its atomic number and its average atomic mass in atomic mass units. Already a great deal has been said, and a number of terms need to be explained. These explanations will require the length of this essay, beginning with a little historical background, because chemists' understanding of the periodic table—and of the elements and atoms it represents—has evolved considerably since 1869.

### Elements and Atoms

An element is a substance that cannot be broken down chemically into another substance. An atom is the smallest particle of an element that retains all the chemical and physical properties of the element, and elements contain only one kind of atom. The scientific concepts of both elements and atoms came to us from the ancient Greeks, who had a rather erroneous notion of the element and—for their time, at least—a highly advanced idea of the atom.

Unfortunately, atomic theory died away in later centuries, while the mistaken notion of four "elements" (earth, air, fire, and water) survived



Dmitri Mendeleev. *(Bettmann/Corbis. Reproduced by permission.)*

virtually until the seventeenth century, an era that witnessed the birth of modern science. Yet the ancients did know of substances later classified as elements, even if they did not understand them as such. Among these were gold, tin, copper, silver, lead, and mercury. These, in fact, are such an old part of human history that their discoverers are unknown. The first individual credited with discovering an element was German chemist Hennig Brand (c. 1630-c. 1692), who discovered phosphorus in 1674.

**Maturing concepts of atoms, elements, and molecules.** The work of English physicist and chemist Robert Boyle (1627-1691) greatly advanced scientific understanding of the elements. Boyle maintained that no substance was an element if it could be broken down into other substances: thus air, for instance, was not an element. Boyle's studies led to the identification of numerous elements in the years that followed, and his work influenced French chemists Antoine Lavoisier (1743-1794) and Joseph-Louis Proust (1754-1826), both of whom helped define an element in the modern sense. These men in turn influenced English chemist John Dalton (1766-1844), who reintroduced atomic theory to the language of science.

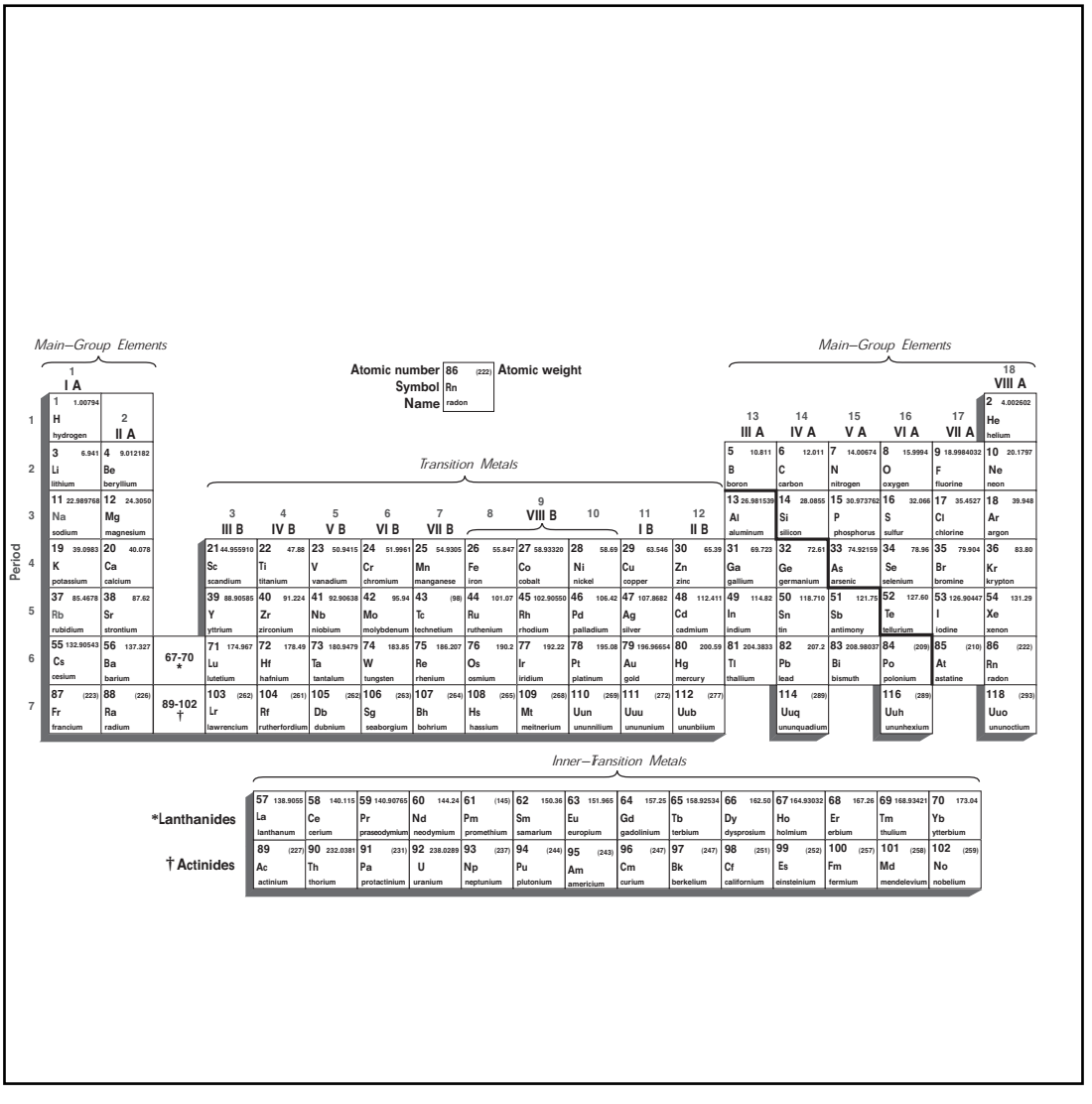
In *A New System of Chemical Philosophy* (1808), Dalton put forward the idea that nature is composed of tiny particles, and in so doing he adopted the Greek word *atomos* to describe these basic units. Drawing on Proust's law of constant composition, Dalton recognized that the structure of atoms in a particular element or compound is uniform, but maintained that compounds are made up of compound "atoms." In fact, these compound atoms are really molecules, or groups of two or more atoms bonded to one another, a distinction clarified by Italian physicist Amedeo Avogadro (1776-1856).

Dalton's and Avogadro's contemporary, Swedish chemist Jons Berzelius (1779-1848), developed a system of comparing the mass of various atoms in relation to the lightest one, hydrogen. Berzelius also introduced the system of chemical symbols—H for hydrogen, O for oxygen, and so on—in use today. Thus, by the middle of the nineteenth century, scientists understood vastly more about elements and atoms than they had just a few decades before, and the need for a system of organizing elements became increasingly clear. By mid-century, a number of chemists had attempted to create just such an organizational system, and though Mendeleev's was not the first, it proved the most useful.

## Mendeleev Constructs His Table

By the time Mendeleev constructed his periodic table in 1869, there were 63 known elements. At that point, he was working as a chemistry professor at the University of St. Petersburg, where he had become acutely aware of the need for a way of classifying the elements to make their relationships more understandable to his students. He therefore assembled a set of 63 cards, one for each element, on which he wrote a number of identifying characteristics for each.

Along with the element symbol, discussed below, he included the atomic mass for the atoms of each. In Mendeleev's time, atomic mass was understood simply to be the collective mass of a unit of atoms—a unit developed by Avogadro, known as the mole—divided by Avogadro's number, the number of atoms or molecules in a mole. With the later discovery of subatomic particles, which in turn made possible the discovery of isotopes, figures for atomic mass were clarified, as will also be discussed.




THE PERIODIC TABLE (IUPAC SYSTEM)

In addition, Mendeleev also included figures for specific gravity—the ratio between the density of an element and the density of water—as well as other known chemical characteristics of an element. Today, these items are typically no longer included on the periodic table, partly for considerations of space, but partly because chemists' much greater understanding of the properties of atoms makes it unnecessary to clutter the table with so much detail.

Again, however, in Mendeleev's time there was no way of knowing about these factors. As far as chemists knew in 1869, an atom was an indivisible little pellet of matter that could not be characterized by terms any more detailed than its mass and the ways it interacted with atoms of other elements. Mendeleev therefore arranged his cards in order of atomic mass, then grouped elements that showed similar chemical properties.

**CONFIDENT PREDICTIONS.** As Mendeleev observed, every eighth element on the chart exhibits similar characteristics, and thus, he established columns whereby element number *x* was placed above element number *x* + *8*—for instance, helium (2) above neon (10). The patterns he observed were so regular that for any "hole" in his table, he predicted that an element to fill that space would be discovered.

Indeed, Mendeleev was so confident in the basic soundness of his organizational system that in some instances, he changed the figures for the atomic mass of certain elements because he was convinced they belonged elsewhere on the table.

Later discoveries of isotopes, which in some cases affected the average atomic mass considerably, confirmed his suppositions. Likewise the undiscovered elements he named "eka-aluminum," "eka-boron," and "eka-silicon" were later identified as gallium, scandium, and germanium, respectively.

## REAL-LIFE APPLICATIONS

### Subatomic Structures Clarify the Periodic Table

Over a period of 35 years, between the discovery of the electron in 1897 and the discovery of the neutron in 1932, chemists' and physicists' understanding of atomic structure changed completely. The man who identified the electron was English physicist J. J. Thomson (1856-1940). The electron is a negatively charged particle that contributes little to an atom's mass; however, it has a great deal to do with the energy an atom possesses. Thomson's discovery made it apparent that something else had to account for atomic mass, as well as the positive electric charge offsetting the negative charge of the electron.

Thomson's student Ernest Rutherford (1871-1937)—for whom, incidentally, rutherfordium (104 on the periodic table) is named—identified that "something else." In a series of experiments, he discovered that the atom has a nucleus, a center around which electrons move, and that the nucleus contains positively charged particles called protons. Protons have a mass 1,836 times as great as that of an electron, and thus, this seemed to account for the total atomic mass.

**Isotopes and atomic mass.** Later, working with English chemist Frederick Soddy (1877-1956), Rutherford discovered that when an atom emitted certain types of particles, its atomic mass changed. Rutherford and Soddy named these atoms of differing mass isotopes, though at that point—because the neutron had yet to be discovered—they did not know exactly what change had caused the change in mass. Certain types of isotopes, Soddy and Rutherford went on to conclude, had a tendency to decay by emitting particles or gamma rays, moving (sometimes over a great period of time) toward stabilization. In the process, these radioactive isotopes changed into other isotopes of the same element—and sometimes even to isotopes of other elements.

Soddy concluded that atomic mass, as measured by Berzelius, was actually an average of the mass figures for all isotopes within that element. This explained a problem with Mendeleev's periodic table, in which there seemed to be irregularities in the increase of atomic mass from element to element. The answer to these variations in mass, it turned out, related to the number of isotopes associated with a given element: the greater the number of isotopes, the more these affected the overall measure of the element's mass.

**A clearer definition of atomic number.** Just a few years after Rutherford and Soddy discovered isotopes, Welsh physicist Henry Moseley (1887-1915) uncovered a mathematical relationship between the amount of energy a given element emitted and its atomic number. Up to this point, the periodic table had assigned atomic number in order of mass, beginning with the lightest element, hydrogen. Using atomic mass and other characteristics as his guides, Mendeleev had been able to predict the discovery of new elements, but such predictions had remained problematic. Thanks to Moseley's work, it became possible to predict the existence of undiscovered elements with much greater accuracy.

As Moseley discovered, the atomic number corresponds to the number of positive charges in the nucleus. Thus carbon, for instance, has an atomic number of 6 not because there are five lighter elements—though this is also true—but because it has six protons in its nucleus. The ordering by atomic number happens to correspond to the ordering by atomic mass, but atomic number provides a much more precise means of distinguishing elements. For one thing, atomic number is always a whole integer—1 for hydrogen, for instance, or 17 for chlorine, or 92 for uranium. Figures for mass, on the other hand, are almost always rendered with whole numbers and decimal fractions (for example, 1.008 for hydrogen).

If atoms have no electric charge, meaning that they have the same number of protons as electrons, then why do chemists not say that atomic number represents the number of protons or electrons? The reason is that electrons can easily be lost or gained by atoms to form ions,

which have an electric charge. However, protons are very hard to remove.

**NEUTRONS AND ATOMIC MASS.** By 1932, scientists had come a long way toward understanding the structure of the atom. Not only had the electron, nucleus, and proton been discovered, but the complex model of electron configuration (described later in this essay) had begun to evolve. Yet, one nagging question remained: the mass of the protons in the nucleus simply could not account for the entire mass of the atom. Neither did the electrons make a significant contribution to mass.

Suppose a proton was "worth" $1,836, while an electron had a value of only $1. In the "bank account" for deuterium, an isotope of hydrogen, there is $3,676, which poses a serious discrepancy in accounting. Because deuterium is a form of hydrogen, it has one proton as well as one electron, but that only accounts for $1,837. Where does deuterium get the other $1,839? These numbers are not chosen at random, as we shall see.

The answer to the problem of atomic mass came when English physicist James Chadwick (1891-1974) identified the neutron, a particle with no electric charge, residing in the nucleus alongside the protons. Whereas the proton has a mass 1,836 times as large as that of the electron, the neutron's mass is slightly larger—1,839 times that of an electron. This made it possible to clarify the values of atomic mass, which up to that time had been problematic, because a mole of atoms representing one element is likely to contain numerous isotopes.

## Average Atomic Mass

Today, the periodic table lists, along with chemical symbol and atomic number, the average atomic mass of each element. As its name suggests, the average atomic mass provides the average value of mass—in atomic mass units (amu)—for a large sample of atoms. According to Berzelius's system for measuring atomic mass, 1 amu should be equal to the mass of a hydrogen atom, even though that mass had yet to be measured, since hydrogen almost never appears alone in nature. Today, in accordance with a 1960 agreement among members of the international scientific community, measurements of atomic mass take carbon-12, an isotope found in all living things, as their reference point.

It is inconvenient, to say the least, to measure the mass of a single carbon-12 atom, or indeed of any other atom. Instead, chemists use a large number of atoms, a value known as Avogadro's number, which in general is the number of atoms in a mole (abbreviated mol). Avogadro's number is defined as $6.02214199 \cdot 10^{23}$, with an uncertainty of $4.7 \cdot 10^{16}$. In other words, the number of particles in a mole could vary by as much as 47,000,000,000,000,000 on either side of the value for Avogadro's number. This might seem like a lot, but in fact it is equal to only about 80 parts per billion.

When 1 is divided by Avogadro's number, the result is $1.66 \cdot 10^{-24}$—the value, in grams, of 1 amu. However, according to the 1960 agreement, 1 amu is officially 1/12 the mass of a carbon-12 atom, whose exact value (re-tested in 1998), is $1.6653873 \times 10^{-24}$ g. Carbon-12, sometimes represented as (12/6)C, contains six protons and six neutrons, so the value of 1 amu thus obtained is, in effect, an average of the mass for a proton and neutron.

Though atoms differ, subatomic particles do not. There is no such thing, for instance, as a "hydrogen proton"—otherwise, these subatomic particles, and not atoms, would constitute the basic units of an element. Given the unvarying mass of subatomic particles, combined with the fact that the neutron only weighs 0.16% more than a proton, the established value of 1 amu provides a convenient means of comparing mass. This is particularly useful in light of the large numbers of isotopes—and hence of varying figures for mass—that many elements have.

**ATOMIC MASS UNITS AND THE PERIODIC TABLE.** The periodic table as it is used today includes figures in atomic mass units for the average mass of each atom. As it turns out, Berzelius was not so far off in his use of hydrogen as a standard, since its mass is almost exactly 1 amu—but not quite. The value is actually 1.008 amu, reflecting the presence of slightly heavier deuterium isotopes in the average sample of hydrogen

Figures increase from hydrogen along the periodic table, though not by a regular pattern. Sometimes the increase from one element to the next is by just over 1 amu, and in other cases, the

increase is by more than 3 amu. This only serves to prove that atomic number, rather than atomic mass, is a more straightforward means of ordering the elements.

Mass figures for many elements that tend to appear in the form of radioactive isotopes are usually shown in parentheses. This is particularly true for elements with very, very high atomic numbers (above 92), because samples of these elements do not stay around long enough to be measured. Some have a half-life—the period in which half the isotopes decay to a stable form—of just a few minutes, and for others, the half-life is a fraction of a second. Therefore, atomic mass figures represent the mass of the longest-lived isotope.

## Elements

As of 2001, there were 112 known elements, of which about 90 occur naturally on Earth. Uranium, with an atomic number of 92, was the last naturally occurring element discovered: hence some sources list 92 natural elements. Other sources, however, subtract those elements with a lower atomic number than uranium that were first created in laboratories rather than discovered in nature. In any case, all elements with atomic numbers higher than 92 are synthetic, meaning that they were created in laboratories. Of these 20 elements—all of which have appeared only in the form of radioactive isotopes with short half-lives—the last three have yet to receive permanent names.

In addition, three other elements—designated by atomic numbers 114, 116, and 118, respectively—are still on the drawing board, as it were, and do not yet even have temporary names. The number of elements thus continues to grow, but these "new" elements have little to do with the daily lives of ordinary people. Indeed, this is true even for some of the naturally occurring elements: for example, few people who are not chemically trained would be able to identify yttrium, which has an atomic number of 39.

Though an element can exist theoretically as a gas, liquid, or a solid, in fact, the vast majority of elements are solids. Only 11 elements exist in the gaseous state at a normal temperature of about 77°F (25°C). These are the six noble gases; fluorine and chlorine from the halogen family; as well as hydrogen, nitrogen, and oxygen. Just two are liquids at normal temperature: mercury, a metal, and the nonmetal halogen bromine. It should be noted that the metal gallium becomes liquid at just 85.6°F (29.76°C); below that temperature, however, it— like the elements other than those named in this paragraph—is a solid.

## Chemical Names and Symbols

For the sake of space and convenience, elements are listed on the periodic table by chemical symbol or element symbol—a one-or two-letter abbreviation for the name of the element according to the system first developed by Berzelius. These symbols, which are standardized and unvarying for any particular element, greatly aid the chemist in writing out chemical formulas, which could otherwise be quite cumbersome.

Many of the chemical symbols are simple one-letter designations: H for hydrogen, O for oxygen, and F for fluorine. Others are two-letter abbreviations, such as He for helium, Ne for neon, and Si for silicon. Note that the first letter is always capitalized, and the second is always lowercase. In many cases, the two-letter symbols indicate the first and second letters of the element's name, but this is not nearly always the case. Cadmium, for example, is abbreviated Cd, while platinum is Pt.

Many of the one-letter symbols indicate elements discovered early in history. For instance, carbon is represented by C, and later "C" elements took two-letter designations: Ce for cerium, Cr for chromium, and so on. Likewise, krypton had to take the symbol Kr because potassium had already been assigned K. The association of potassium with K brings up one of the aspects of chemical symbols most confusing to students just beginning to learn about the periodic table: why K and not P? The latter had in fact already been taken by phosphorus, but then why not Po, assigned many years later instead to polonium?

**Chemical symbols based in other languages.** In fact, potassium's symbol is one of the more unusual examples of a chemical symbol, taken from an ancient or non-European language. Soon after its discovery in the early nineteenth century, the element was named kalium, apparently after the Arabic *qali* or "alkali." Hence, though it is known as potassium today, the old symbol still stands.

The use of Arabic in naming potassium is unusual in the sense that "strange" chemical symbols usually refer to Latin and Greek names. Latin names include *aurum,* or "shining dawn" for gold, symbolized as Au; or *ferrum,* the Latin word for iron, designated Fe. Likewise, lead (Pb) and sodium (Na) are represented by letters from their Latin names, *plumbum* and *natrium,* respectively.

Some chemical elements are named for Greek or German words describing properties of the element. Consider, for instance, the halogens, collectively named for a Greek term meaning "salt producing." *Chloros,* in Greek, describes a sickly yellow color, and was assigned to chlorine; the name of bromine comes from a Greek word meaning "stink"; and that of iodine is a form of a Greek term meaning "violet-colored." Astatine, last-discovered of the halogens and the rarest of all natural elements, is so radioactive that it was given a name meaning "unstable." Another Greek-based example outside the halogen family is phosphorus, or "I bring light"—appropriate enough, in view of its phosphorescent properties.

**NAMES OF LATER ELEMENTS.** The names of several elements with high atomic numbers—specifically, the lanthanides, the transuranium elements of the actinide series, and some of the later transition metals—have a number of interesting characteristics. Several reflect the places where they were originally discovered or created: for example, germanium, americium, and californium. Other elements are named for famous or not-so-famous scientists. Most people could recognize einsteinium as being named after Albert Einstein (1879-1955), but the origin of the name gadolinium—Finnish chemist Johan Gadolin (1760-1852)—is harder for the average person to identify. Then of course there is element 101, named mendelevium in honor of the man who created the periodic table.

Two elements are named after women: curium after French physicist and chemist Marie Curie (1867-1934), and meitnerium after Austrian physicist Lise Meitner (1878-1968). Curie, the first scientist to receive two Nobel Prizes—in both physics and chemistry—herself discovered two elements, radium and polonium. In keeping with the trend of naming transuranium elements after places, she commemorated the land of her birth, Poland, in the name of polonium. One of Curie's students, French physicist Marguerite Perey (1909-1975), also discovered an element and named it after her own homeland: francium.

Meitnerium, the last element to receive a name, was created in 1982 at the Gesellschaft für Schwerionenforschung, or GSI, in Darmstadt, Germany, one of the world's three leading centers of research involving transuranium elements. The other two are the Joint Institute for Nuclear Research in Dubna, Russia, and the University of California at Berkeley, for which berkelium is named.

**THE IUPAC AND THE NAMING OF ELEMENTS.** One of the researchers involved with creating berkelium was American nuclear chemist Glenn T. Seaborg (1912-1999), who discovered plutonium and several other transuranium elements. In light of his many contributions, the scientists who created element 106 at Dubna in 1974 proposed that it be named seaborgium, and duly submitted the name to the International Union of Pure and Applied Chemistry (IUPAC).

Founded in 1919, the IUPAC is, as its name suggests, an international body, and it oversees a number of matters relating to the periodic table: the naming of elements, the assignment of chemical symbols to new elements, and the certification of a particular research team as the discoverers of that element. For many years, the IUPAC refused to recognize the name seaborgium, maintaining that an element could not be named after a living person. The dispute over the element's name was not resolved until the 1990s, but finally the IUPAC approved the name, and today seaborgium is included on the international body's official list.

Elements 110 through 112 had yet to be named in 2001, and hence were still designated by the three-letter symbols Uun, Uuu, and Uub respectively. These are not names, but alphabetic representations of numbers: un for 1, nil for 0, and bium for 2. Thus, the names are rendered as ununnilium, unununium, and ununbium; the undiscovered elements 114, 116, and 118 are respectively known as ununquadium, ununhexium, and ununoctium.

## Layout of the Periodic Table

**TWO SYSTEMS FOR LABELING GROUPS.** Having discussed the three items of

information contained in the boxes of the periodic table—atomic number, chemical symbol/name, and average atomic mass—it is now possible to step back from the chart and look at its overall layout. To reiterate what was stated in the introduction to the periodic table above, the table is arranged in rows called periods, and columns known as groups. The deeper meaning of the periods and groups, however—that is, the way that chemists now understand them in light of what they know about electron configurations—will require some explanation.

All current versions of the periodic table show seven rows—in other words, seven periods—as well as 18 columns. However, the means by which columns are assigned group numbers varies somewhat. According to the system used in North America, only eight groups are numbered. These are the two "tall" columns on the left side of the "dip" in the chart, as well as the six "tall" columns to the right of it. The "dip," which spans 10 columns in periods 4 through 7, is the region in which the transition metals are listed. The North American system assigns no group numbers to these, or to the two rows set aside at the bottom, representing the lanthanide and actinide series of transition metals.

As for the columns that the North American system does number, this numbering may appear in one of four forms: either by Roman numerals; Roman numerals with the letter A (for example, IIIA); Hindu-Arabic numbers (for example, 3); or Hindu-Arabic numerals with the letter A. Throughout this book, the North American system of assigning Hindu-Arabic numerals without the letter A has been used. However, an attempt has been made in some places to include the group designation approved by the IUPAC, which is used by scientists in Europe and most parts of the world outside of North America. (Some scientists in North America are also adopting the IUPAC system.)

The IUPAC numbers all columns on the chart, so that instead of eight groups, there are 18. The table below provides a means of comparing the North American and IUPAC systems. Columns are designated in terms of the element family or families, followed in parentheses by the atomic numbers of the elements that appear at the top and bottom of that column. The first number following the colon is the number in the North American system (as described above, a Hindu-Arabic numerical without an "A"), and the second is the number in the IUPAC system.

| Element Family | North American | IUPAC |
|---|---|---|
| Hydrogen and alkali metals (1, 87) | 1 | 1 |
| Alkaline metals (4, 88) | 2 | 2 |
| Transition metals (21,89) | | 3 |
| Transition metals (22,104) | | 4 |
| Transition metals (23,105) | | 5 |
| Transition metals (24,106) | | 6 |
| Transition metals (25,107) | | 7 |
| Transition metals (26,108) | | 8 |
| Transition metals (27,109) | | 9 |
| Transition metals (28,110) | | 10 |
| Transition metals (29,111) | | 11 |
| Transition metals (30,112) | | 12 |
| Nonmetals and metals (5,81) | 3 | 13 |
| Nonmetals, metalloids, and metal (6,82) | 4 | 14 |
| Nonmetals, metalloids, and metal (7,83) | 5 | 15 |
| Nonmetals, metalloids, (8,84) | 6 | 16 |
| Halogens (9,85) | 7 | 17 |
| Noble gases (2,86) | 8 | 18 |
| Lanthanides (58,71) | No number group assigned in either system | |
| Actinides (90,103) | No number group assigned in either system | |

## Valence Electrons, Periods, and Groups

The merits of the IUPAC system are easy enough to see: just as there are 18 columns, the IUPAC lists 18 groups. Yet the North American system is more useful than it might seem: the group number in the North American system indicates the number of valence electrons, the electrons that are involved in chemical bonding. Valence electrons also occupy the highest energy level in the atom—which might be thought of as the orbit farthest from the nucleus, though in fact the reality is more complex.

A more detailed, though certainly far from comprehensive, discussion of electrons and energy levels, as well as the history behind these discoveries, appears in the Electrons essay. In what follows, the basics of electron configuration will be presented with the specific aim of making it clear exactly why elements appear in particular columns of the periodic table.

**PRINCIPAL ENERGY LEVELS AND PERIODS.** At one time, scientists thought that electrons moved around a nucleus in regular orbits, like planets around the Sun. In fact the paths of an electron are much more complicated, and can only be loosely defined in terms of orbitals, a set of probabilities regarding the positions that an electron is likely to occupy as it moves around the nucleus. The pattern of orbitals is determined by the principal energy level of the atom, which indicates a distance that an electron may move away from the nucleus.

Principal energy level is designated by a whole-number integer, beginning with 1 and moving upward: the higher the number, the further the electron is from the nucleus, and hence the greater the energy in the atom. Each principal energy level is divided into sublevels corresponding to the number *n* of the principal energy level: thus, principal energy level 1 has one sublevel, principal energy level 2 has two, and so on.

The relationship between principal energy level and period is relatively easy to demonstrate: the number *n* of a period on the periodic table is the same as the number of the highest principal energy level for the atoms on that row—that is, the principal energy level occupied by its valence electrons. Thus, elements on period 4 have a highest principal energy level of 4, whereas the valence electrons of elements on period 7 are at principal energy level 7. Note the conclusion that this allows us to draw: the further down the periodic table an element is positioned, the greater the energy in a single atom of that element. Not surprisingly, most of the elements used in nuclear power come from period 7, which includes the actinides.

**VALENCE ELECTRON CONFIGURATIONS AND GROUPS.** Now to a more involved subject, whereby group number is related to valence electron configuration. As mentioned earlier, the principal energy levels are divided into sublevels, which are equal in number to the principal energy level number: principal energy level 1 has one sublevel, level 2 has two sublevels, and so on. As one might expect, with an increase in principal energy levels and sublevels, there are increases in the complexity of the orbitals.

The four types of orbital patterns are designated as *s, p,d,* and *f.* Two electrons can move in an *s* orbital pattern or shell, six in a *p,* 10 in a *d,* and 14 in an *f* orbital pattern or shell. This says nothing about the number of electrons that are actually in a particular atom; rather, the higher the principal energy level and the larger the number of sublevels, the greater the number of ways that the electrons can move. It does happen to be the case, however, that with higher atomic numbers—which means more electrons to offset the protons—the higher the energy level, the larger the number of orbitals for those electrons.

Let us now consider a few examples of valence shell configurations. Hydrogen, with the simplest of all atomic structures, has just one electron on principal energy level 1, so in effect its valence electron is also a core electron. The valence configuration for hydrogen is thus written as $1s^1$. Moving straight down the periodic table to francium (atomic number 87), which is in the same column as hydrogen, one finds that it has a valence electron configuration of $7s^1$. Thus, although francium is vastly more complex and energy-filled than hydrogen, the two elements have the same valence-shell configuration; only the number of the principal energy level is different.

Now look at two elements in Group 3 (Group 13 in the IUPAC system): boron and thallium, which respectively occupy the top and bottom of the column, with atomic numbers of 5 and 81. Boron has a valence-shell configuration of $2s^2 2p^1$. This means its valence shell is at principal energy level 2, where there are two electrons in an *s* orbital pattern, and 2 in a *p* orbital pattern. Thallium, though it is on period 6, nonetheless has the same valence-shell configuration: $6s^2 6p^1$.

Notice something about the total of the superscript figures for any element in Group 3 of the North American system: it is three. The same is true in the other columns numbered on North American charts, in which the total number of electrons equals the group number. Thus in Group 7, the valence shell configuration is $ns^2 np^5$, where *n* is the principal energy level. There is only one exception to this: helium, in Group 8 (the noble gases), has a valence shell configuration of $1s^2$. Were it not for the fact that it clearly fits with the noble gases due to shared properties, helium would be placed next to hydrogen at the top of Group 2, where all the atoms have a valence-shell configuration of $ns^2$.

Obviously the group numbers in the IUPAC system do not correspond to the number of valence electrons, because the IUPAC chart includes numbers for the columns of transition metals, which are not numbered in the North American system. In any case, in both systems the columns contain elements that all have the same number of electrons in their valence shells. Thus the term "group" can finally be defined in accordance with modern chemists' understanding, which incorporates electron configurations of which Mendeleev was unaware. All the members of a group have the same number of valence electrons in the same orbital patterns, though at different energy levels. (Once again, helium is the lone exception.)

## Some Challenges of the Periodic Table

**irregular patterns.** The groups that are numbered in the North American system are referred to as "representative" elements, because they follow a clearly established pattern of adding valence shell electrons. By contrast, the 40 elements listed in the "dip" at the middle of the chart—the transition elements—do not follow such a pattern. This is why the North American system does not list them by group number, and also why neither system lists two "branches" of the transition-metal family, the lanthanides and actinides.

Even within the representative elements, there are some challenges as far as electron configuration. For the first 18 elements—1 (hydrogen) to 18 (argon)—there is a regular pattern of orbital filling. Beginning with helium (2) onward, all of principal level 1 is filled; then, beginning with beryllium (4), sublevel 2*s* begins to fill. Sublevel 2*p*—and hence principal level 2 as a whole—becomes filled at neon (10).

After argon, as one moves to the element occupying the nineteenth position on the periodic table—potassium—the rules change. Argon, in Group 8 of the North American system, has a valence shell of $3s^2 3p^6$, and by the pattern established with the first 18 elements, potassium should begin filling principal level 3*d*. Instead, it "skips" 3*d* and moves on to 4*s*. The element following argon, calcium, adds a second electron to the 4*s* sublevel.

After calcium, as the transition metals begin with scandium (21), the pattern again changes: indeed, the transition elements are defined by the fact that they fill the *d* orbitals rather than the *p* orbitals, as was the pattern up to that point. After the first period of transition metals ends with zinc (30), the next representative element—gallium (31)—resumes the filling of the *p* orbital rather than the *d*. And so it goes, all along the four periods in which transition metals break up the steady order of electron configurations.

As for the lanthanide and actinide series of transitions metals, they follow an even more unusual pattern, which is why they are set apart even from the transition metals. These are the only groups of elements that involve the highly complex *f* sublevels. In the lanthanide series, the seven 4*f* orbital shells are filled, while the actinide series reflects the filling of the seven 5*f* orbital shells.

Why these irregularities? One reason is that as the principal energy level increases, the energy levels themselves become closer—i.e., there is less difference between the energy levels. The atom is thus like a bus that fills up: when there are just a few people on board, those few people (analogous to electrons) have plenty of room, but as more people get on, the bus becomes increasingly more crowded, and passengers jostle against one another. In the atom, due to differences in energy levels, the 4*s* orbital actually has a lower energy than the 3*d,* and therefore begins to fill first. This is also true for the 6*s* and 4*f* orbitals.

**changes in atomic size.** The subject of element families is a matter unto itself, and therefore a separate essay in this book has been devoted to it. The reader is encouraged to consult the Families of Elements essay, which discusses aspects of electron configuration as well as the properties of various element families.

One last thing should be mentioned about the periodic table: the curious fact that the sizes of atoms decreases as one moves from left to right across a row or period, even though the sizes increase as one moves from top to bottom along a group. The increase of atomic size in a group, as a function of increasing atomic number, is easy enough to explain. The higher the atomic number, the higher the principal energy level, and the greater the distance from the nucleus to the furthest probability range for the electron.

On the other hand, the decrease in size across a period is a bit more challenging to com-

## KEY TERMS

**ATOM:** The smallest particle of an element that retains all the chemical and physical properties of the element.

**ATOMIC MASS UNIT:** An SI unit (abbreviated amu), equal to $1.66 \cdot 10^{-24}$ 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 of elements 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.

**AVOGADRO'S NUMBER:** A figure, named after Italian physicist Amedeo Avogadro (1776-1856), equal to $6.022137 \times 10^{23}$. Avogadro's number indicates the number of atoms or molecules in a mole.

**CHEMICAL SYMBOL:** A one- or two-letter abbreviation for the name of an element.

**COMPOUND:** A substance made of two or more elements that have bonded chemically. These atoms are usually, but not always, joined in molecules.

**ELECTRON:** A negatively charged particle in an atom. The configurations of valence electrons define specific groups on the periodic table of elements, while the principal energy levels of those valence electrons define periods on the table.

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

**ELEMENT SYMBOL:** Another term for chemical symbol.

**GROUPS:** Columns on the periodic table of elements. These are ordered according to the numbers of valence electrons in the outer shells of the atoms for the elements represented.

**HALF-LIFE:** The length of time it takes a substance to diminish to one-half its initial amount.

**ION:** An atom or atoms that has lost or gained one or more electrons, thus acquiring 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. Isotopes may be either stable or unstable. The latter type, known as radioisotopes, are radioactive.

**MOLE:** The SI fundamental unit for "amount of substance." A mole is, generally speaking, Avogadro's number of atoms, molecules, or other elementary particles; however, in the more precise SI definition, a mole is equal to the number of carbon atoms in 12.01 g of carbon.

**MOLECULE:** A group of atoms, usually but not always representing more than one element, joined by chemical bonds. Compounds are typically made of up molecules.

**NEUTRON:** A subatomic particle that has no electric charge. Neutrons, together with protons, account for the majority of average atomic mass. When atoms have the same number of protons—and hence are the same element—but differ in their number of neutrons, they are called isotopes.

## KEY TERMS CONTINUED

**NUCLEUS:** The center of an atom, a region where protons and neutrons are located. The nucleus accounts for the vast majority of the average atomic mass.

**ORBITAL:** A pattern of probabilities regarding the regions that an electron can occupy within an atom in a particular energy state. The higher the principal energy level, the more complex the pattern of orbitals.

**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 (in atomic mass units) for that particular element.

**PERIODS:** Rows of the periodic table of elements. These represent successive principal energy levels for the valence electrons in the atoms of the elements involved.

**PRINCIPAL ENERGY LEVEL:** A value indicating the distance that an electron may move away from the nucleus of an atom. This is designated by a whole-number integer, beginning with 1 and moving upward. The higher the principal energy level, the greater the energy in the atom, and the more complex the pattern of orbitals.

**PROTON:** A positively charged particle in an atom. The number of protons in the nucleus of an atom is the atomic number of an element.

**RADIOACTIVITY:** A term describing a phenomenon whereby certain isotopes known as radioisotopes are subject to a form of decay brought about by the emission of high-energy particles. "Decay" does not mean that the isotope "rots"; rather, it decays to form another isotope— either of the same element or another—until eventually it becomes stable. This stabilizing process may take a few seconds, or many years.

**VALENCE ELECTRONS:** Electrons that occupy the highest energy levels in an atom. These are the electrons involved in chemical bonding.

prehend; however, it just takes a little explaining. As one moves along a period from left to right, there is a corresponding increase in the number of protons within the nucleus. This means a stronger positive charge pulling the electrons inward. Therefore, the "cloud" of electrons is drawn ever closer toward the increasingly powerful charge at the center of the atom, and the size of the atom decreases because the electrons cannot move as far away from the nucleus.

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# FAMILIES OF ELEMENTS

## CONCEPT

The term "family" is used to describe elements that share certain characteristics—not only in terms of observable behavior, but also with regard to atomic structure. All noble gases, for instance, tend to be highly nonreactive: only a few of them combine with other elements, and then only with fluorine, the most reactive of all substances. Fluorine is a member of another family, the halogens, which have so many shared characteristics that they are grouped together, despite the fact that two are gases, two are solids, and one—bromine—is one of only two elements that appears at room temperature as a solid. Despite these apparent differences, common electron configurations identify the halogens as a family. Families on the periodic table include, in addition to noble gases and halogens, the alkali metals, alkaline earth metals, transition metals, lanthanides, and actinides. The nonmetals form a loosely defined cross-family grouping, as do the metalloids.

## HOW IT WORKS

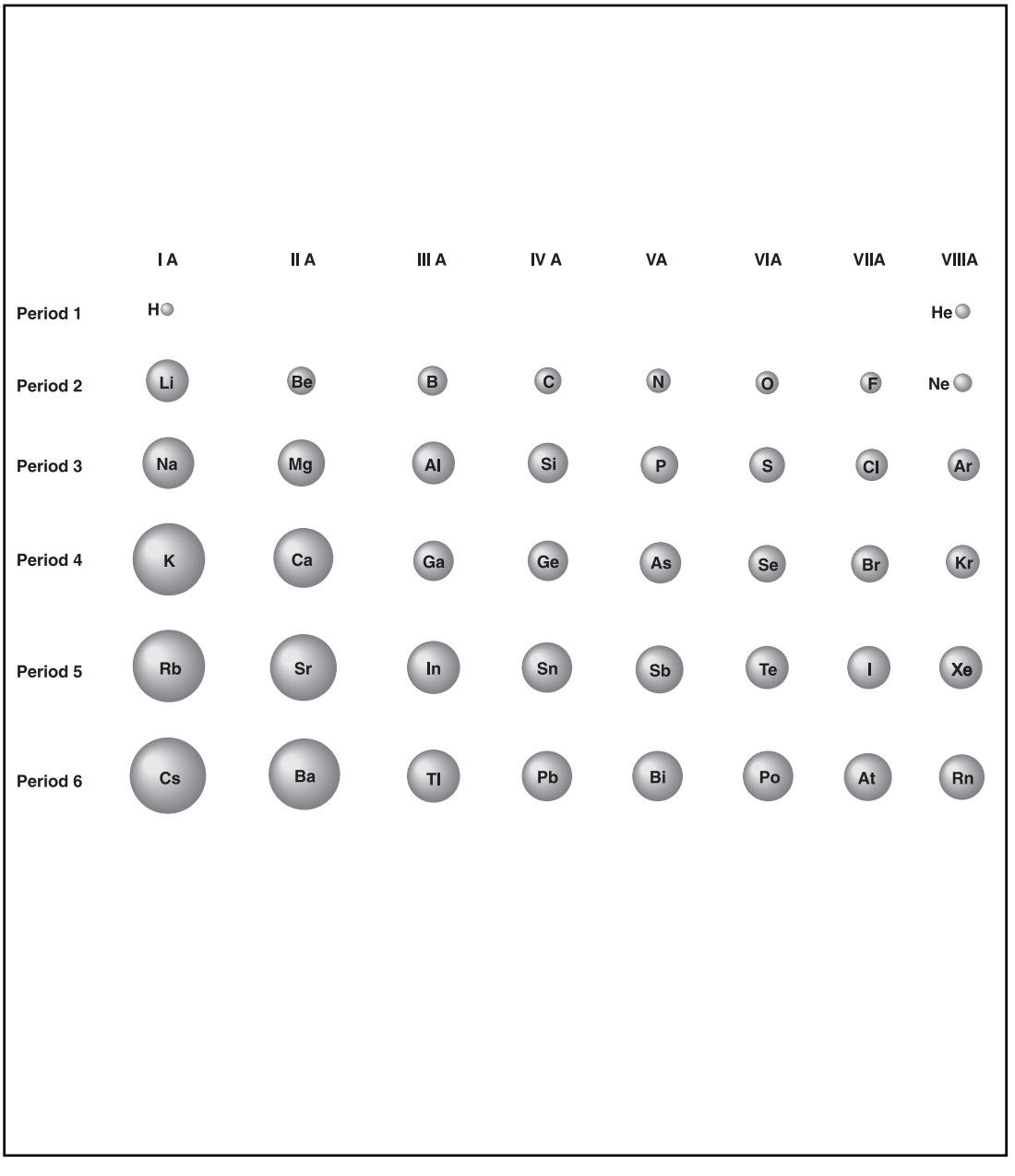
### The Basics of the Periodic Table

Created in 1869, and modified several times since then, the periodic table of the elements developed by Russian chemist Dmitri Ivanovitch Mendeleev (1834-1907) provides a highly useful means of organizing the elements. Certainly other organizational systems exist, but Mendeleev's table is the most widely used—and with good reason. For one thing, it makes it possible to see at a glance families of elements, many of which either belong to the same group (column) or the same period (row) on the table.

The periodic table is examined in depth within the essay devoted to that subject, and among the specifics discussed in that essay are the differing systems used for periodic-table charts in North America and the rest of the world. In particular, the North American system numbers only eight groups, leaving 10 columns unnumbered, whereas the other system—approved by the International Union of Pure and Applied Chemistry (IUPAC)—numbers all 18 columns. Both versions of the periodic table show seven periods.

The groups numbered in the North American system are the two "tall" columns on the left side of the "dip" in the chart, as well as the six "tall" columns to the right of it. Group 1 in this system consists of hydrogen and the alkali metals; Group 2, the alkaline earth metals; groups 3 through 6, an assortment of metals, nonmetals, and metalloids; Group 7, halogens; and Group 8, noble gases. The "dip," which spans 10 columns in periods 4 through 7, is the region in which the transition metals are listed. The North American system assigns no group numbers to these, or to the two rows set aside at the bottom, representing the lanthanide and actinide series of transition metals.

The IUPAC system, on the other hand, offers the obvious convenience of providing a number for each column. (Note that, like its North American counterpart, the IUPAC chart provides no column numbers for the lanthanides or actinides.) Furthermore, the IUPAC has behind it the authority of an international body, founded in 1919, which oversees a number of matters




Size representation of the atomic radii of the main-group elements.

relating to the periodic table: the naming of elements, the assignment of chemical symbols to new elements, and the certification of a particular individual or research team as the discoverers of that element. For these reasons, the IUPAC system is coming into favor among North American chemists as well.

Despite the international acceptance of the IUPAC system, as well as its merits in terms of convenience, the North American system is generally the one used in this book. The reason, in part, is that most American schools still use this system; furthermore, there is a reasoning behind the assignment of numbers to only eight groups, as will be discussed. Where necessary or appropriate, however, group numbers in the IUPAC system will be provided as well.

## Principal Energy Levels

Group numbers in the North American system indicate the number of valence electrons, or the electrons that are involved in chemical bonding.

Valence electrons also occupy the highest energy level in the atom—which might be thought of as the orbit farthest from the nucleus, though in fact the term "orbit" is misleading when applied to the ways an electron moves.

Electrons do not move around the nucleus of an atom in regular orbits, like planets around the Sun; rather, their paths can only be loosely defined in terms of orbitals, a pattern of probabilities regarding the areas through which an electron is likely to move. The pattern of orbitals is determined by the principal energy level of the atom, which indicates the distance an electron may move away from the nucleus.

Principal energy level is designated by a whole-number integer, beginning with 1 and moving upward to 7: the higher the number, the further the electron is from the nucleus, and hence the greater the energy in the atom. The relationship between principal energy level and period is relatively easy to demonstrate. The number *n* of a period on the periodic table is the same as the number of the highest principal energy level for the atoms on that row—that is, the principal energy level occupied by its valence electrons. Thus, elements on period 1 have a highest principal energy level of 1, and so on.

### Valence Electron Configurations

When discussing families of elements, however, the periods or rows on the periodic table are not as important as the groups or columns. These are defined by the valence electron configurations, a subject more complicated than principal energy levels—though the latter requires a bit more explanation in order to explain electron configurations.

Each principal energy level is divided into sublevels corresponding to the number *n* of the principal energy level: thus, principal energy level 1 has one sublevel, principal energy level 2 has two, and so on. As one might expect, with an increase in principal energy levels and sublevels, there are increases in the complexity of the orbitals.

**orbital patterns.** The four basic types of orbital patterns are designated as *s, p,d,* and *f.* The *s* shape might be described as spherical, though when talking about electrons, nothing is quite so neat: orbital patterns, remember, only identify regions of probability for the electron. In other words, in an *s* orbital, the total electron cloud will probably end up being more or less like a sphere.

The *p* shape is like a figure eight around the nucleus, and the *d* like two figure eights meeting at the nucleus. Again, these and other orbital patterns do not indicate that the electron will necessary follow that path. What it means is that, if you could take millions of photographs of the electron during a period of a few seconds, the resulting blur of images in a *p* orbital would somewhat describe the shape of a figure eight.

The *f* orbital pattern is so complex that most basic chemistry textbooks do not even attempt to explain it, and beyond *f* are other, even more complicated, patterns designated in alphabetical order: *g, h,* and so on. In the discussion that follows, we will not be concerned with these, since even for the lanthanides and the actinides, an atom at the ground state does not fill orbital patterns beyond an *f.*

**sublevels and orbital filling.** Principal energy level 1 has only an *s* sublevel; 2 has an *s* and a *p,* the latter with three possible orientations in space; 3 has an *s, p,* and *d* (five possible spatial orientations); and 4 has an *s, p, d,* and *f* (seven possible spatial orientations.)

According to the Pauli exclusion principle, only two electrons can occupy a single orbital pattern—that is, the *s* sublevel or any one of the spatial orientations in *p, d,* and *f*—and those two electrons must be spinning in opposite directions. Thus, two electrons can move in an *s* orbital pattern or shell, six in a *p,* 10 in a *d,* and 14 in an *f* orbital pattern or shell. Valence shell configurations are therefore presented with superscript figures indicating the number of electrons in that orbital pattern—for instance, $s^1$ for one electron in the *s* orbital, or $d^{10}$, indicating a *d* orbital that has been completely filled.

## Real-Life Applications

### Representative Elements

Hydrogen (atomic number 1), with the simplest of all atomic structures, has just one electron on principal energy level 1, so, in effect, its valence electron is also a core electron. The valence configuration for hydrogen is thus written as $1s^1$. It should be noted, as described in the Electrons

essay, that if a hydrogen atom (or any other atom) is in an excited state, it may reach energy levels beyond its normal, or ground, state.

Moving straight down the periodic table to francium (atomic number 87), which is in the same column as hydrogen, one finds that it has a valence electron configuration of $7s^1$. Thus, although francium is vastly more complex and energy-filled than hydrogen, the two elements have the same valence shell configuration; only the number of the principal energy level is different. All the elements listed below hydrogen in Group 1 are therefore classified together as alkali metals. Obviously, hydrogen—a gas—is not part of the alkali metal family, nor does it clearly belong to any other family: it is the "lone wolf" of the periodic table.

Now look at two elements in Group 2, with beryllium (atomic number 4) and radium (88) at the top and bottom respectively. Beryllium has a valence shell configuration of $2s^2$. This means its valence shell is at principal energy level 2, where there are two electrons on an *s* orbital pattern. Radium, though it is on period 7, nonetheless has the same valence shell configuration: $7s^2$. This defines the alkaline earth metals family in terms of valence shell configuration.

For now, let us ignore groups 3 through 6—not to mention the columns between groups 2 and 3, unnumbered in the North American system—and skip over to Group 7. All the elements in this column, known as halogens, have valence shell configurations of $ns^2np^5$. Beyond Group 7 is Group 8, the noble gases, all but one of whom have valence shell configurations of $ns^2np^6$. The exception is helium, which has an $s^2$ valence shell. This seems to put it with the alkaline earth metals, but of course helium is not a metal. In terms of its actual behavior, it clearly belongs to the noble gases family.

The configurations of these valence shells have implications with regard to the ways in which elements bond, a subject developed at some length in the Chemical Bonding essay. Here we will consider it only in passing, to clarify the fact that electron configuration produces observable results. This is most obvious with the noble gases, which tend to resist bonding with most other elements because they already have eight electrons in their valence shell—the same number of valence electrons that most other atoms achieve only after they have bonded.

## From the Representative Elements to the Transition Elements

Groups 3 through 6, along with hydrogen and the four families so far identified, constitute the 44 representative or main-group elements. In 43 of these 44, the number of valence shell electrons is the same as the group number in the North American system. (Helium, which is in Group 8 but has two valence electrons, is the lone exception.) By contrast, the 40 elements listed in the "dip" at the middle of the chart—the transition metals—follow a less easily defined pattern. This is part of the reason why the North American system does not list them by group number, and also why neither system lists the two other families within the transition elements—the lanthanides and actinides.

Before addressing the transition metals, however, let us consider patterns of orbital filling, which also differentiate the representative elements from the transition elements. Each successive representative element fills all the orbitals of the elements that precede it (with some exceptions that will be explained), then goes on to add one more possible electron configuration. The total number of electrons—not just valence shell electrons—is the same as the atomic number. Thus fluorine, with an atomic number of 9, has a complete configuration of $1s^22s^22p^5$. Neon, directly following it with an atomic number of 10, has a total configuration of $1s^22s^22p^6$. (Again, this is not the same as the valence shell configuration, which is contained in the last two sublevels represented: for example, $2s^22p^6$ for neon.)

The chart that follows shows the pattern by which orbitals are filled. Note that in several places, the pattern of filling becomes "out of order," something that will be explained below.

Orbital Filling by Principal Energy Level

- $1s$ (2)
- $2s$ (2)
- $2p$ (6)
- $3s$ (2)
- $3p$ (6)
- $4s$ (2)
- $3d$ (10)
- $4p$ (6)
- $5s$ (2)
- $4d$ (10)
- $5p$ (6)

- 6*s* (2)
- 4*f* (14)
- 5*d* (10)
- 6*p* (6)
- 7*s* (2)
- 5*f* (14)
- 6*d* (10)

**PATTERNS OF ORBITAL FILLING.** Generally, the 44 representative elements follow a regular pattern of orbital filling, and this is particularly so for the first 18 elements. Imagine a small amphitheater, shaped like a cone, with smaller rows of seats at the front. These rows are also designated by section, with the section number being the same as the number of rows in that section.

The two seats in the front row comprise a section labeled 1 or 1*s,* and this is completely filled after helium (atomic number 2) enters the auditorium. Now the elements start filling section 2, which contains two rows. The first row of section 2, labeled 2*s,* also has two seats, and after beryllium (4), it too is filled. Row 2*p* has 6 seats, and it is finally filled with the entrance of neon (10). Now, all of section 2 has been filled; therefore, the eleventh element, sodium, starts filling section 3 at the first of its three rows. This row is 3*s*—which, like all *s* rows, has only two seats. Thus, when element 13, aluminum, enters the theatre, it takes a seat in row 3*p,* and eventually argon (18), completes that six-seat row.

By the pattern so far established, element 19 (potassium) should begin filling row 3*d* by taking the first of its 10 seats. Instead, it moves on to section 4, which has four rows, and it takes the first seat in the first of those rows, 4*s.* Calcium (20) follows it, filling the 4*s* row. But when the next element, scandium (21), comes into the theatre, it goes to row 3*d,* where potassium "should have" gone, if it had continued filling sections in order. Scandium is followed by nine companions (the first row of transition elements) before another representative element, gallium (31), comes into the theatre. (For reasons that will not be discussed here, chromium and copper, elements 24 and 29, respectively, have valence electrons in 4*s*—which puts them slightly off the transition metal pattern.)

According to the "proper" order of filling seats, now that 3*d* (and hence all of section 3) is filled, gallium should take a seat in 4*s*. But those seats have already been taken by the two preceding representative elements, so gallium takes the first of six seats in 4*p.* After that row fills up at krypton (36), it is again "proper" for the next representative element, rubidium (37), to take a seat in 4*d.* Instead, just as potassium skipped 3*d,* rubidium skips 4*d* and opens up section 5 by taking the first of two seats in 5*s.*

Just as before, the next transition element—yttrium (39)—begins filling up section 4*d,* and is followed by nine more transition elements until cadmium (48) fills up that section. Then, the representative elements resume with indium (49), which, like gallium, skips ahead to section 5*p.* And so it goes through the remainder of the periodic table, which ends with two representative elements followed by the last 10 transition metals.

## TRANSITION METALS

Given the fact that it is actually the representative elements that skip the *d* sublevels, and the transition metals that go back and fill them, one might wonder if the names "representative" and "transition" (implying an interruption) should be reversed. However, remember the correlation between the number of valence shell electrons and group number for the representative elements. Furthermore, the transition metals are the only elements that fill the *d* orbitals.

This brings us to the reason why the lanthanides and actinides are set apart even from the transition metals. In most versions of the periodic table, lanthanum (57) is followed by hafnium (72) in the transition metals section of the chart. Similarly, actinium (89) is followed by rutherfordium (104). The "missing" metals—lanthanides and actinides, respectively—are listed at the bottom of the chart. There are reasons for this, as well as for the names of these groups.

After the 6*s* orbital fills with the representative element barium (56), lanthanum does what a transition metal does—it begins filling the 5*d* orbital. But after lanthanum, something strange happens: cerium (58) quits filling 5*d,* and moves to fill the 4*f* orbital. The filling of that orbital continues throughout the entire lanthanide series, all the way to lutetium (71). Thus, lanthanides can be defined as those metals that fill the 4*f* orbital; however, because lanthanum exhibits similar properties, it is usually included with the lanthanides. Sometimes the term "lan-

## KEY TERMS

**ACTINIDES:** Those transition metals that fill the 5*f* orbital. Because actinium—which does not fill the 5*f* orbital—exhibits characteristics similar to those of the actinides, it is usually considered part of the actinides family.

**ALKALI METALS:** All members, except hydrogen, of Group 1 on the periodic table of elements, with valence electron configurations of $ns^1$.

**ALKALINE EARTH METALS:** Group 2 on the periodic table of elements, with valence electron configurations of $ns^2$.

**ELECTRON CLOUD:** A term used to describe the pattern formed by orbitals.

**FAMILIES OF ELEMENTS:** Related elements, including the noble gases, halogens, alkali metals, alkaline earth metals, transition metals,lanthanides, and actinides. In addition, metals, nonmetals, and metalloids form loosely defined families. Other family designations—such as carbon family—are sometimes used.

**GROUND STATE:** A term describing the state of an atom at its ordinary energy level.

**GROUPS:** Columns on the periodic table of elements. These are ordered according to the numbers of valence electrons in the outer shells of the atoms for the elements represented.

**HALOGENS:** Group 7 of the periodic table of elements, with valence electron configurations of $ns^2np^5$.

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

**LANTHANIDES:** The transition metals that fill the 4*f*orbital. Because lanthanum—which does not fill the 4*f* orbital—exhibits characteristics similar to those of the lanthanides, it is usually considered part of the lanthanide family.

**MAIN-GROUP ELEMENTS:** The 44 elements in Groups 1 through 8 on the periodic table of elements, for which the number of valence electrons equals the group number. (The only exception is helium.) The main-group elements, also called representative elements, include the families of alkali metals, alkali earth metals, halogens, and noble gases, as well as other metals, nonmetals, and metalloids.

**METALLOIDS:** Elements which exhibit characteristics of both metals and nonmetals. Metalloids are all solids, but are not lustrous or shiny, and they conduct heat and electricity moderately well. The six metalloids occupy a diagonal region between the metals and nonmetals on the right side of the periodic table. Sometimes astatine is included with the metalloids, but in this book it is treated within the context of the halogens family.

**METALS:** A collection of 87 elements that includes numerous families—the alkali metals, alkaline earth metals, transition metals, lanthanides, and actinides, as well as seven elements in groups 3 through 5. Metals, which occupy the left, center, and part of the right-hand side of the periodic table, are lustrous or shiny in appearance, and malleable, meaning that they can be molded into different shapes without breaking. They are excellent conductors of heat and electricity, and tend to form positive ions by losing electrons.

## KEY TERMS CONTINUED

**NOBLE GASES:** Group 8 of the periodic table of elements, all of whom (with the exception of helium) have valence electron configurations of $ns^2np^6$.

**NONMETALS:** Elements that have a dull appearance; are not malleable; are poor conductors of heat and electricity; and tend to gain electrons to form negative ions. They are thus the opposite of metals in most regards, as befits their name. Aside from hydrogen, the other 18 nonmetals occupy the upper right-hand side of the periodic table, and include the noble gases, halogens, and seven elements in groups 3 through 6.

**ORBITAL:** A pattern of probabilities regarding the position of an electron for an atom in a particular energy state. The higher the principal energy level, the more complex the pattern of orbitals. The four types of orbital patterns are designated as *s, p, d,* and *f*—each of which is more complex than the one before.

**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 (in atomic mass units) for that particular element.

**PERIODS:** Rows of the periodic table of elements. These represent successive energy levels in the atoms of the elements involved.

**PRINCIPAL ENERGY LEVEL:** A value indicating the distance that an electron may move away from the nucleus of an atom. This is designated by a whole-number integer, beginning with 1 and moving upward. The higher the principal energy level, the greater the energy in the atom, and the more complex the pattern of orbitals.

**REPRESENTATIVE ELEMENTS:** See main-group elements.

**TRANSITION METALS:** A group of 40 elements, which are not assigned a group number in the North American version of the periodic table. These are the only elements that fill the *d* orbitals.

**VALENCE ELECTRONS:** Electrons that occupy the highest energy levels in an atom. These are the electrons involved in chemical bonding.

thanide series" is used to distinguish the other 14 lanthanides from lanthanum itself.

A similar pattern occurs for the actinides. The 7*s* orbital fills with radium (88), after which actinium (89) begins filling the 6*d* orbital. Next comes thorium, first of the actinides, which begins the filling of the 5*f* orbital. This is completed with element 103, lawrencium. Actinides can thus be defined as those metals that fill the 5*f* orbital; but again, because actinium exhibits similar properties, it is usually included with the actinides.

### Metals, Nonmetals, and Metalloids

The reader will note that for the seven families so far identified, we have generally not discussed them in terms of properties that can more easily be discerned—such as color, phase of matter, bonding characteristics, and so on. Instead, they have been examined primarily from the standpoint of orbital filling, which provides a solid chemical foundation for identifying families. Macroscopic characteristics, as well as the ways that the various elements find application in

daily life, are discussed within essays devoted to the various groups.

Note, also, that the families so far identified account for only 92 elements out of a total of 112 listed on the periodic table: hydrogen; six alkali metals; six alkaline earth metals; five halogens; six noble gases; 40 transition metals; 14 lanthanides; and 14 actinides. What about the other 20? Some discussions of element families assign these elements, all of which are in groups 3 through 6, to families of their own, which will be mentioned briefly. However, because these "families" are not recognized by all chemists, in this book the 20 elements of groups 3 through 6 are described generally as metals, nonmetals, and metalloids.

**METALS AND NONMETALS.** Metals are lustrous or shiny in appearance, and malleable, meaning that they can be molded into different shapes without breaking. They are excellent conductors of heat and electricity, and tend to form positive ions by losing electrons. On the periodic table, metals fill the left, center, and part of the right-hand side of the chart. Thus it should not come as a surprise that most elements (87, in fact) are metals. This list includes alkali metals, alkaline earth metals, transition metals, lanthanides, and actinides, as well as seven elements in groups 3 through 6—aluminum, gallium, indium, thallium, tin, lead, and bismuth.

Nonmetals have a dull appearance; are not malleable; are poor conductors of heat and electricity; and tend to gain electrons to form negative ions. They are thus the opposite of metals in most regards, as befits their name. Nonmetals, which occupy the upper right-hand side of the periodic table, include the noble gases, halogens, and seven elements in groups 3 through 5. These nonmetal "orphans" are boron, carbon, nitrogen, oxygen, phosphorus, sulfur, and selenium. To these seven orphans could be added an eighth, from Group 1: hydrogen. As with the metals, a separate essay—with a special focus on the "orphans"—is devoted to nonmetals.

**METALLOIDS AND OTHER "FAMILY" DESIGNATIONS.** Occupying a diagonal region between the metals and nonmetals are metalloids, elements which exhibit characteristics of both metals and nonmetals. They are all solids, but are not lustrous, and conduct heat and electricity moderately well. The six metalloids are silicon, germanium, arsenic, antimony, tellurium, and polonium. Astatine is sometimes identified as a seventh metalloid; however, in this book, it is treated as a member of the halogen family.

Some sources list "families" rather than collections of "orphan" metals, metalloids, and nonmetals, in groups 3 through 6. These designations are not used in this book; however, they should be mentioned briefly. Group 3 is sometimes called the boron family; Group 4, the carbon family; Group 5, the nitrogen family; and Group 6, the oxygen family. Sometimes Group 5 is designated as the pnictogens, and Group 6 as the chalcogens.

## WHERE TO LEARN MORE


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# METALS

METALS
ALKALI METALS
ALKALINE EARTH METALS
TRANSITION METALS
ACTINIDES
LANTHANIDES

# METALS

## CONCEPT

A number of characteristics distinguish metals, including their shiny appearance, as well as their ability to be bent into various shapes without breaking. In addition, metals tend to be highly efficient conductors of heat and electricity. The vast majority of elements on the periodic table are metals, and most of these fall into one of five families: alkali metals; alkaline earth metals; the very large transition metals family; and the inner transition metal families, known as the lanthanides and actinides. In addition, there are seven "orphans," or metals that do not belong to a larger family of elements: aluminum, gallium, indium, thallium, tin, lead, and bismuth. Some of these may be unfamiliar to most readers; on the other hand, a person can hardly spend a day without coming into contact with aluminum. Tin is a well-known element as well, though much of what people call "tin" is not really tin. Lead, too, is widely known, and once was widely used as well; today, however, it is known primarily for the dangers it poses to human health.

## HOW IT WORKS

### General Properties of Metals

Metals are 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 and have high melting and boiling points. They are excellent conductors of heat and electricity, and tend to form positive ions by losing electrons.

The bonds that metals form with each other, or with nonmetals, are known as ionic bonds, which are the strongest type of chemical bond. Even within a metal, however, there are extremely strong bonds. Therefore, though it is easy to shape metals (that is, to slide the atoms in a metal past one another), it is very difficult to separate metal atoms. Their internal bonding is thus very strong, but nondirectional.

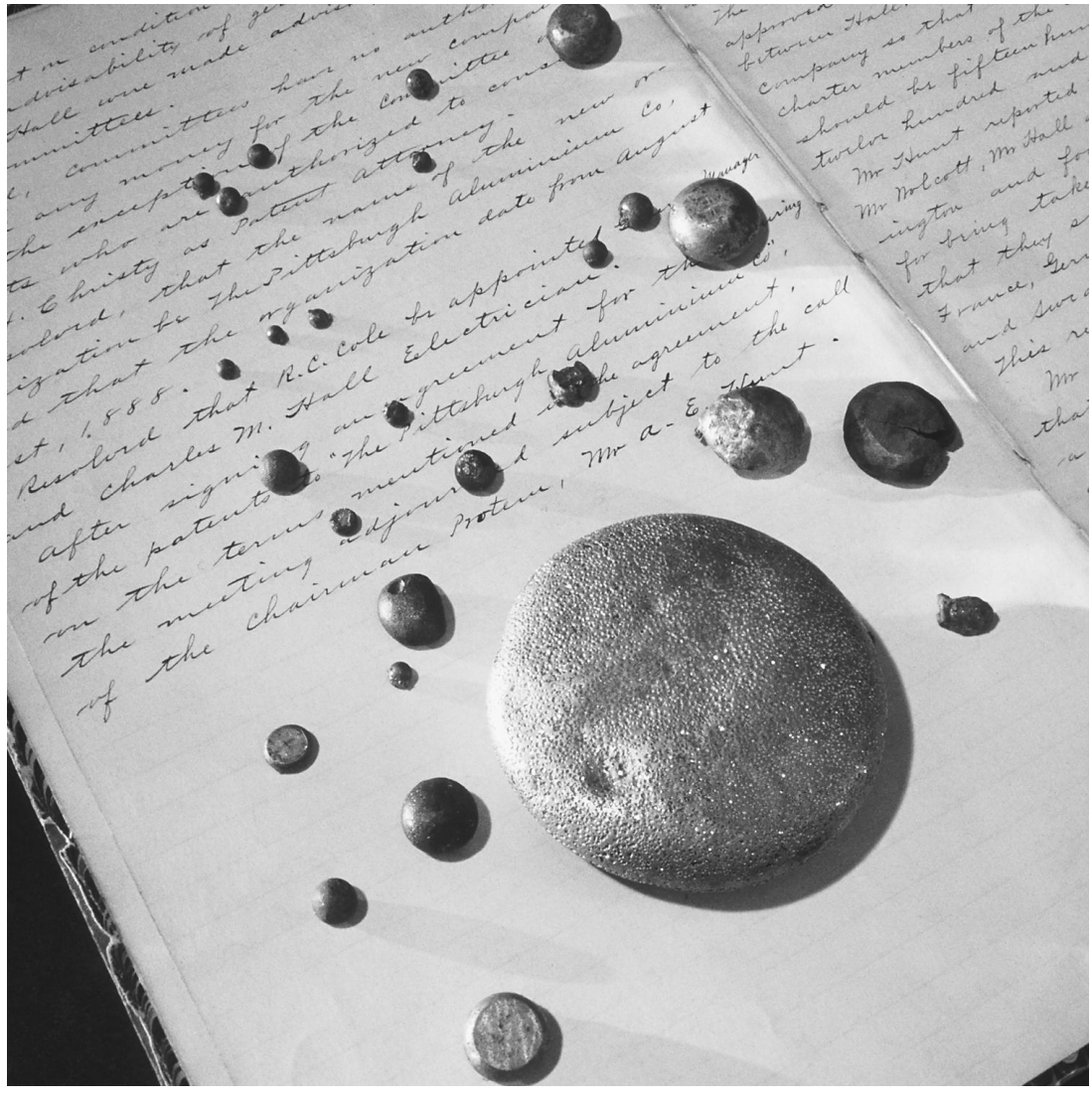
Internal bonding in metals is described by the electron sea model, which depicts metal atoms as floating in a "sea" of valence electrons, the electrons involved in bonding. These valence electrons are highly mobile within the crystalline structure of the metal, and this mobility helps to explain metals' high conductivity. The ease with which metal crystals allow themselves to be rearranged explains not only metals' ductility, but also their ability to form alloys, a mixture containing one or more metals.

### Abundance of Metals

Metals constitute a significant portion of the elements found in Earth's crust, waters, and atmosphere.

The following list shows the most abundant metals on Earth, with their ranking among all elements in terms of abundance. Many other metals are present in smaller, though still significant, quantities.

- 3. Aluminum (7.5%)
- 4. Iron (4.71%)
- 5. Calcium (3.39%)
- 6. Sodium (2.63%)
- 7. Potassium (2.4%)
- 8. Magnesium (1.93%)



Aluminum is the most abundant metal on Earth. This photo shows the first blobs of aluminum ever isolated, a feat performed by Charles Hall in 1886. *(James L. Amos/Corbis. Reproduced by permission.)*

- 10. Titanium (0.58%)
- 13. Manganese (0.09%)

In addition, metals are also important components of the human body. The following list shows the ranking of the most abundant metals among the elements in the body, along with the percentage that each constitutes. As with the quantities of metals on Earth, other metals are present in much smaller, but still critical, amounts.

- 5. Calcium (1.4%)
- 7. Magnesium (0.50%)
- 8. Potassium (0.34%)
- 10. Sodium (0.14%)
- 12. Iron (0.004%)
- 13. Zinc (0.003%)

## Metals on the Periodic Table

On the periodic table of elements, metals fill the left, center, and part of the right-hand side of the chart. The remainder of the right-hand section is taken by nonmetals, which have properties quite different from (and often opposite to) those of metals, as well as metalloids, which display characteristics both of metals and nonmetals. Nonmetallic elements are covered in essays on Nonmetals; Metalloids; Halogens; Noble Gases; and Carbon. In addition, hydrogen, the one nonmetal on the left side of the periodic table—first among the elements, in the upper left corner—is also discussed in its own essay.

The total number of metals on the periodic table is 87—in other words, about 80% of all

known elements. These include the six alkali metals, which occupy Group 1 of the periodic table, as well as the six alkaline earth metals, or Group 2. To the right of these are the 40 transition metals, whose groups are unnumbered in the North American version of the periodic table. Among the transition metals are two elements, lanthanum and actinium, often lumped in with the families of inner transition metals that exhibit similar properties. These are, respectively, the 14 lanthanides and 14 actinides. In addition, there are the seven "orphan" metals of periods 3 through 5, mentioned in the introduction to this essay, which will be discussed below.

The various families of elements are defined, not so much by external characteristics as by the configurations of valence electrons in their atoms' shells. This subject will not be discussed in any depth here; instead, the reader is encouraged to consult essays on the specific metal families, which discuss the electron configurations of each.



BEFORE THEY WERE DESTROYED BY TERRORIST ATTACKS ON SEPTEMBER 11, 2001, THE TWIN TOWERS OF THE WORLD TRADE CENTER IN NEW YORK CITY GLEAMED WITH A CORROSION-RESISTANT COVERING OF ALUMINUM. *(Bill Ross/Corbis. Reproduced by permission.)*

## REAL-LIFE APPLICATIONS

### Alkali Metals

The members of the alkali metal family are distinguished by the fact that they have a valence electron configuration of $s^1$ This means that they tend to bond easily with other substances. Alkali metals tend to form positive ions, or cations, with a charge of 1+.

In contact with water, alkali metals form a negatively charged hydroxide ion ($OH^-$). When alkali metals react with water, one hydrogen atom splits off from the water molecule to form hydrogen gas, while the other hydrogen atom remains bonded to the oxygen, forming hydroxide. Where the heavier members of the alkali metal family are concerned, reactions can often be so vigorous that the result is combustion or even explosion. Alkali metals also react with oxygen to produce either an oxide, peroxide, or superoxide, depending on the particular member of the alkali metal family involved.

Shiny and soft enough to be cut with a knife, the alkali metals are usually white, though cesium is a yellowish white. When placed in a flame, most of these substances produce characteristic colors: lithium, for instance, glows bright red, and sodium an intense yellow. Heated potassium produces a violet color, rubidium a dark red, and cesium a light blue. This makes it possible to identify the metals by color when heated—a useful trait, since they so often tend to be bonded with other elements.

The alkali metals, listed below by atomic number and chemical symbol, are:

- 3. Lithium (Li)
- 11. Sodium (Na)
- 19. Potassium (K)
- 37. Rubidium (Rb)
- 55. Cesium (Cs)
- 87. Francium (Fr)

### Alkaline Earth Metals

Occupying Group 2 of the periodic table are the alkaline earth metals, which have a valence electron configuration of $s^2$. Like the alkali metals, the alkaline earth metals are known for their high reactivity—a tendency for bonds between atoms or molecules to be made or broken in such a way that materials are transformed. Thus they are sel-



Most "tin" roofs now consist of an iron or steel roof covered with zinc, not tin. *(John Hulme; Eye Ubiquitous/Corbis. Reproduced by permission.)*

dom found in pure form, but rather in compounds with other elements—for example, salts, a term that generally describes a compound consisting of a metal and a nonmetal.

The alkaline earth metals are also like the alkali metals in that they have the properties of a base as opposed to an acid. An acid is a substance that, when dissolved in water, produces positive ions of hydrogen, designated symbolically as $H^+$ ions. It is thus known as a proton donor. A base, on the other hand, produces negative hydroxide ions when dissolved in water. These are designated by the symbol $OH^-$. Bases are therefore characterized as proton acceptors.

The alkaline earth metals are shiny, and most are white or silvery in color. Like their "cousins" in the alkali metal family, they glow with characteristic colors when heated. Calcium glows orange, strontium a very bright red, and barium an apple green. Physically they are soft, though not as soft as the alkali metals; nor are their levels of reactivity as great as those of their neighbors in Group 1.

The alkaline earth metals, listed below by atomic number and chemical symbol, are:

- 4. Beryllium (Be)
- 12. Magnesium (Mg)
- 20. Cadmium (Ca)
- 38. Strontium (Sr)
- 56. Barium (Ba)
- 88. Radium (Ra)

## Transition Metals

The transition metals are the only elements that fill the dorbitals. They are also the only elements that have valence electrons on two different principal energy levels. This sets them apart from the representative or main-group elements, of which the alkali metals and alkaline earth metals are a part. The transition metals also follow irregular patterns of orbital filling, which further distinguish them from the representative elements.

Other than that, there is not much that differentiates the transition metals, a broad grouping that includes precious metals such as gold, silver, and platinum, as well as highly functional metals such as iron, manganese, and zinc. Many of the transition metals, particularly those on periods 4, 5, and 6, form useful alloys with one another, and with other elements. Because of their differences in valence electron configuration, however, they do not always combine in the same ways, even within an element. Iron, for

instance, sometimes releases two electrons in chemical bonding, and at other times three.

**GROUPING THE TRANSITION METALS.** There is no easy way to group the transition metals, though some of these elements are traditionally categorized together. These do not constitute "families" as such, but they do provide useful ways to break down the otherwise rather daunting lineup of the transition metals. In two cases, there is at least a relationship between group number on the periodic table and the categories loosely assigned to a collection of transition metals. Thus the "coinage metals"—copper, silver, and gold—all occupy Group 9 on the IUPAC version of the periodic table. (These have traditionally been associated with one another because their resistance to oxidation, combined with their malleability and beauty, has made them useful materials for fashioning coins.

Likewise the members of the "zinc group"—zinc, cadmium, and mercury—on Group 10 on the IUPAC periodic table have often been associated as a miniature unit due to common properties. Members of the "platinum group"—platinum, iridium, osmium, palladium, rhodium, and ruthenium—occupy a rectangle on the table, corresponding to periods 5 and 6, and groups 6 through 8. What actually makes them a "group," however, is the fact that they tend to appear together in nature. Iron, nickel, and cobalt, found alongside one another on Period 4, may be grouped together because they are all magnetic to some degree.

The transition metals, listed below by atomic number and chemical symbol, are:

- 21. Scandium (Sc)
- 22. Titanium (Ti)
- 23. Vanadium (V)
- 24. Chromium (Cr)
- 25. Manganese (Mn)
- 26. Iron (Fe)
- 27. Cobalt (Co)
- 28. Nickel (Ni)
- 29. Copper (Cu)
- 30. Zinc (Zn)
- 39. Yttrium (Y)
- 40. Zirconium (Zr)
- 41. Niobium (Nb)
- 42. Molybdenum (Mo)
- 43. Technetium (Tc)
- 44. Ruthenium (Ru)
- 45. Rhodium (Rh)
- 46. Palladium (Pd)
- 47. Silver (Ag)
- 48. Cadmium (Cd)
- 57. Lanthanum (La)
- 72. Hafnium (Hf)
- 73. Tantalum (Ta)
- 74. Tungsten (W)
- 75. Rhenium (Re)
- 76. Osmium (Os)
- 77. Iridium (Ir)
- 78. Platinum (Pt)
- 79. Gold (Au)
- 80. Mercury (Hg)
- 89. Actinium (Ac)
- 104. Rutherfordium (Rf)
- 105. Dubnium (Db)
- 106. Seaborgium (Sg)
- 107. Bohrium (Bh)
- 108. Hassium (Hs)
- 109. Meitnerium (Mt)
- 110. Ununnilium (Uun)
- 111. Unununium (Uuu)
- 112. Ununbium (Uub)

The last nine, along with 11 of the actinides, are part of the list of metals known collectively as the transuranium elements—that is, elements with atomic numbers higher than 92. These have all been produced artificially, in most cases within a laboratory. Note that the last three had not been named as of 2001: the "names" by which they are known simply mean, respectively, 110, 111, and 112.

## LANTHANIDES

The lanthanides are the first of two inner transition metal groups. Note that in the list of transition metals above, lanthanum (57) is followed by hafnium (72). The "missing" group of 14 elements, normally shown at the bottom of the periodic table, is known as the lanthanides, a family which can be defined by the fact that all fill the 4f orbital. However, because lanthanum (which does not fill an f orbital) exhibits similar properties, it is usually included with the lanthanides.

Bright and silvery in appearance, many of the lanthanides—though they are metals—are so soft they can be cut with a knife. They also tend to be highly reactive. Though they were once known as the "rare earth metals," lanthanides

only seemed rare because they were difficult to extract from compounds containing other substances—including other lanthanides. Because their properties are so similar, and because they tend to be found together in the same substances, the original isolation and identification of the lanthanides was an arduous task that took well over a century.

The lanthanides (in addition to lanthanum, listed earlier with the transition metals), are:

- 58. Cerium (Ce)
- 59. Praseodymium (Pr)
- 60. Neodymium (Nd)
- 61. Promethium (Pm)
- 62. Samarium (Sm)
- 63. Europium (Eu)
- 64. Gadolinium (Gd)
- 65. Terbium (Tb)
- 66. Dysprosium (Dy)
- 67. Holmium (Ho)
- 68. Erbium (Er)
- 69. Thulium (Tm)
- 70. Ytterbium (Yb)
- 71. Lutetium (Lu)

## ACTINIDES

Just as lanthanum is followed on the periodic table by an element with an atomic number 15 points higher, so actinium (89) is followed by rutherfordium (104). The elements in the "gap" are the other inner transition family, the actinides, which all fill the 5f orbital. These are placed below the lanthanides at the bottom of the chart, and just as lanthanum is included with the lanthanides, even though it does not fill an f orbital, so actinium is usually lumped in with the actinides due to similarities in properties.

Most of the actinides tend to be unstable or radioactive, the later ones highly so. The first three members of the group (not counting actinium) occur in nature, while the other 11 are transuranium elements created artificially. In most cases, these were produced with a cyclotron or other machine for accelerating atoms, generally at the research center of the University of California at Berkeley during a period from 1940 to 1961. Einsteinium and fermium, however, were by-products of nuclear testing at Bikini Atoll in the south Pacific in 1952. The principal use of the actinides is in nuclear applications—weaponry or power plants—though some of them also have specialized uses as well.

The actinides (in addition to actinium, listed earlier with the transition metals), are:

- 90. Thorium (Th)
- 91. Protactinium (Pa)
- 92. Uranium (U)
- 93. Neptunium (Np)
- 94. Plutonium (Pu)
- 95. Americium (Am)
- 96. Curium (Cm)
- 97. Berkelium (Bk)
- 98. Californium (Cf)
- 99. Einsteinium (Es)
- 100. Fermium (Fm)
- 101. Mendelevium (Md)
- 102. Nobelium (No)
- 103. Lawrencium (Lr)

## "ORPHAN" METALS

Seven other metals remain to be discussed. These are the "orphan" metals, which appear in groups 3, 4, and 5 of the North American periodic table (13, 14, and 15 of the IUPAC table), and they are called "orphans" simply because none belongs to a clearly defined family. Sometimes aluminum and the three elements below it in Group 3—gallium, indium, and thallium—are lumped together as the "aluminum family." This is not a widely recognized distinction, but will be used here only for the purpose of giving some form of organization to the "orphan" elements.

Though they do not belong to families, the "orphan" metals are nonetheless highly important. Aluminum, after all, is the most abundant of all metals on Earth, and has wide applications in daily life. Tin, too, is widely known, as is lead. Somewhat less recognizable is bismuth, but it appears in a product with which most Americans are familiar: Pepto-Bismol.

The seven "orphans" are listed below, along with atomic number and chemical symbol:

- 13. Aluminum (Al)
- 31. Gallium (Ga)
- 49. Indium (In)
- 50. Tin (Sn)
- 81. Thallium (Tl)
- 82. Lead (Pb)
- 83. Bismuth (Bi)

## ALUMINUM

Named after alum, a salt known from ancient times and used by the Egyptians, Romans, and Greeks, aluminum is so reactive that it proved difficult to isolate. Only in 1825 did Danish physicist Hans Christian Ørsted (1777-1851) isolate an impure version of aluminum metal, using a complicated four-step process. Two years later, German chemist Friedrich Wöhler (1800-1882) obtained pure aluminum from a reaction of metallic potassium with aluminum chloride, or $AlCl_3$.

For years thereafter, aluminum continued to be so difficult to produce that it acquired the status of a precious metal. European kings displayed treasures of aluminum as though they were gold or silver, and by 1855, it was selling for about $100,000 a pound. Then in 1886, French metallurgist Paul-Louis-Toussaint Héroult (1863-1914) and American chemist Charles Martin Hall (1863-1914) independently developed a process that made aluminum relatively easy to extract by means of electrolysis. Thanks to what became known as the Hall-Héroult process, the price of aluminum dropped to around 30 cents a pound.

America's aluminum comes primarily from mines in Alabama, Arkansas, and Georgia, where it often appears in a clay called kaolin, used in making porcelain. Aluminum can also be found in deposits of feldspar, mica, granite, and other clays. The principal sources of aluminum outside the United States include France, Surinam, Jamaica, and parts of Africa.

**USES FOR ALUMINUM.** Though aluminum is highly reactive, it does not corrode in moist air. Instead of forming rust the way iron does, it forms a thin, hard, invisible coating of aluminum oxide. This, along with its malleability, makes it highly useful for producing cans and other food containers. The World Trade Center Towers in New York City gleam with a corrosion-resistant covering of aluminum. Likewise the element is used as a coating for mirrors: not only is it cheaper than silver, but unlike silver, it does not tarnish and turn black. Also, a thin coating of metallic aluminum gives Mylar balloons their silvery sheen.

Aluminum conducts electricity about 60% as well as copper, meaning that it is an extraordinarily good conductor, useful for transmitting electrical power. Because it is much more lightweight than copper and highly ductile, it is often used in high-voltage electric lines. Its conductivity also makes aluminum a favorite material for kitchen pots and pans. Unlike copper, it is not known to be toxic; however, because aluminum dissolves in strong acids, sometimes tomatoes and other acidic foods acquire a "metallic" taste when cooked in an aluminum pot.

Though it is soft in its pure form, when combined with copper, manganese, silicon, magnesium, and/or zinc, aluminum can produce strong, highly useful alloys. These find application in automobiles, airplanes, bridges, highway signs, buildings, and storage tanks. Aluminum's high ductility also makes it the metal of choice for foil wrappings—that is, aluminum foil. Compounds containing aluminum are used in a wide range of applications, including antacids; antiperspirants (potassium aluminum sulfate tends to close up sweat-gland ducts); and water purifiers.

## OTHER ELEMENTS IN THE ALUMINUM GROUP

**GALLIUM.** When Russian chemist Dmitri Ivanovitch Mendeleev (1834-1907) created the periodic table in 1869, he predicted the existence of several missing elements on the basis of "holes" between elements on the table. Among these was what he called "eka-aluminum," discovered in the 1870s by French chemist Paul Emile Lecoq de Boisbaudran (1838-1912). Boisbaudran named the new element gallium, after the ancient name of his homeland, Gaul.

Gallium will melt if held in the hand, and remains liquid over a large range of temperatures—from 85.6°F (29.76°C) to 3,999.2°F (2,204°C). This makes it highly useful for thermometers with a large temperature range. Used in a number of applications within the electronics industry, gallium is present in the compounds gallium arsenide and gallium phosphide, applied in lasers, solar cells, transistors, and other solid-state devices.

**INDIUM AND THALLIUM.** As Boisbaudran would later do, German mineralogists Ferdinand Reich (1799-1882) and Hieronymus Theodor Richter (1824-1898) used a method called spectroscopy to discover one of the aluminum-group metals. Spectroscopy involves analyzing the frequencies of light (that is, the colors) emitted by an item of matter.

However, Reich faced a problem when studying the zinc ores that he believed contained a new element: he was colorblind. Therefore he called on the help of Richter, his assistant. In 1863, they discovered an element they called indium because of the indigo blue color it emitted. Reich later tried to claim that he made the discovery alone, but Richter's role is indisputable.

Indium is used in making alloys, one of which is a combination with gallium that is liquid at room temperature. Its alloys are used in bearings, dental amalgams, and nuclear control roles. Various compounds are applied in solid-state electronics devices, and in electronics research.

Two years before the discovery of indium, English physicist William Crookes (1832-1919) discovered another element using spectroscopic analysis. This was thallium, named after the Greek word thallos ("green twig"), a reference to a lime-green spectral line that told Crookes he had found a new element. Thallium is applied in electronic equipment, and the compound thallium sulfate is used for killing ants and rodents.

## Three Other "Orphans"

**TIN.** Known from ancient times, tin was combined with copper to make bronze—an alloy so significant it defines an entire stage of human technological development. Tin's chemical symbol, Sn, refers to the name the Romans gave it: stannum. Just as tin added to copper gave bronze its strength, alloys of tin with copper and antimony created pewter, a highly useful, malleable material for pots and dinnerware popular from the thirteenth century through the early nineteenth century.

Tin is found primarily in Bolivia, Malaysia, Indonesia, Thailand, Zaire, and Nigeria—a wide geographical range. Like aluminum today, it has been widely used as a coating for other metals to retard corrosion. Hence the term "tin can," referring to a steel can coated with tin. Also, tin has been used to coat iron or steel roofs, but because zinc is cheaper, it is now most often the coating of choice; nonetheless, these are still typically called "tin roofs."

**LEAD.** Due to knowledge of its toxic properties, lead is not frequently used today, but this was not always the case. The Romans, for instance, used plumbum as they called it (hence the chemical symbol Pb) as a material for making water pipes. This is the root of our own word plumber. (The same root explains the verb plumb or the noun plumb bob. A plumb bob is a lead weight, hung from a string, used to ensure that the walls of a structure are "plumb"—that is, perpendicular to the foundation.) Many historians believe that plumbum in the Romans' water supply was one of the reasons behind the decline and fall of the Roman Empire.

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; reduction in the synthesis of hemoglobin, which carries oxygen from the lungs to the blood and organs; and decreased ability to utilize vitamin D and calcium for strengthening bones. Higher concentrations of lead can effect the central nervous system, resulting in decreased mental functioning and hearing damage. Prolonged exposure can result in a coma or even death.

Before these facts became widely known in the late twentieth century, lead was applied as an ingredient in paint. In addition, it was used in water pipes, and as an anti-knock agent in gasolines. Increased awareness of the health hazards involved have led to a discontinuation of these practices. (Note that pencil "lead" is actually graphite, a form of carbon.)

Lead, however, is used for absorbing radiation—for instance, as a shield against X rays. Another important use for lead today is in storage batteries. Yet another "application" of lead relates to its three stable isotopes (lead-206, -207, and -208), the end result of radioactive decay on the part of various isotopes of uranium and other radioactive elements.

**BISMUTH.** During the Middle Ages, when a number of unscientific ideas prevailed, scholars believed that lead eventually became tin, tin eventually turned into bismuth, and bismuth developed into silver. Hence they referred to bismuth as "roof of silver." Only in the sixteenth century did German metallurgist Georgius Agricola (George Bauer; 1494-1555) put forward the idea that bismuth was a separate element.

Bismuth appears in nature not only in its elemental form, but also in a number of compounds and ores. It is also obtained as a by-product from the smelting of gold, silver, copper, and lead. Because bismuth expands dramatically when it cools, early printers used a bismuth alloy

## KEY TERMS

**ACTINIDES:** Those transition metals that fill the 5f orbital. Because actinium—which does not fill the *f* orbital—exhibits characteristics similar to those of the actinides, it is usually considered part of the actinides family.

**ALKALI METALS:** All members, ex-cept hydrogen, of Group 1 on the periodic table of elements, with valence electron configurations of $ns^1$.

**ALKALINE EARTH METALS:** Group 2 on the periodic table of elements, with valence electron configurations of $ns^2$.

**ALLOY:** A mixture containing more than one metal.

**CONDUCTIVITY:** The ability to conduct heat or electricity. Metals are noted for their high levels of conductivity.

**CRYSTALLINE:** A term describing an internal structure in which the constituent parts have a simple and definite geometric arrangement, repeated in all directions. Metals have a crystalline structure.

**DUCTILE:** Capable of being bent or molded into various shapes without breaking.

**ELECTRON SEA MODEL:** A widely accepted model of internal bonding within metals, which depicts metal atoms as floating in a "sea" of valence electrons.

**GROUPS:** Columns on the periodic table of elements. These are ordered according to the numbers of valence electrons in the outer shells of the atoms for the elements represented.

**INNER TRANSITION METALS:** The lanthanides and actinides, both of which fill the f orbitals. For this reason, they are usually treated as distinct from the transition metals.

**ION:** An atom or group of atoms 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. Isotopes may be either stable or unstable. The latter type, known as radioisotopes, are radioactive.

**IUPAC SYSTEM:** A version of the periodic table of elements, authorized by the International Union of Pure and Applied Chemistry (IUPAC), which numbers all groups on the table from 1 to 18. Thus in the IUPAC system, in use primarily outside of North America, both the representative or main-group elements and the transition metals are numbered.

**LANTHANIDES:** The transition metals that fill the 4f orbital. Because lanthanum—which does not fill the f orbital—exhibits characteristics similar to those of the lanthanides, it is usually considered part of the lanthanide family.

**METALS:** A collection of 87 elements that includes numerous families—the alkali metals, alkaline earth metals, transition metals, lanthanides, and actinides, as well as seven elements in groups 3 through 5 of the North American system periodic table. Metals are lustrous or shiny in appearance, and ductile. They are excellent conductors of heat and electricity, and tend to form positive ions by losing electrons.

## KEY TERMS CONTINUED

**NORTH AMERICAN SYSTEM:** A version of the periodic table of elements that only numbers groups of elements in which the number of valence electrons equals the group number. Hence the transition metals are usually not numbered in this system.

**ORBITAL:** A pattern of probabilities regarding the position of an electron for an atom in a particular energy state. The higher the principal energy level, the more complex the pattern of orbitals.

**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. Elements are arranged in groups or columns, as well as in rows or periods, according to specific aspects of their valence electron configurations.

**PERIODS:** Rows on the periodic table of elements. These represent successive principal energy levels for the valence electrons in the atoms of the elements involved.

**PRINCIPAL ENERGY LEVEL:** A value indicating the distance that an electron may move away from the nucleus of an atom. This is designated by a whole-number integer, beginning with 1 and moving upward. The higher the principal energy level, the greater the energy in the atom, and the more complex the pattern of orbitals.

**RADIOACTIVITY:** A term describing a phenomenon whereby certain isotopes known as radioisotopes are subject to a form of decay brought about by the emission of high-energy particles. "Decay" does not mean that the isotope "rots"; rather, it decays to form another isotope until eventually (though this may take a long time) it becomes stable.

**REACTIVITY:** The tendency for bonds between atoms or molecules to be made or broken in such a way that materials are transformed.

**REPRESENTATIVE OR MAIN-GROUP ELEMENTS:** The 44 elements in Groups 1 through 8 on the North American version of periodic table of elements, for which the number of valence electrons equals the group number. (The only exception is helium.) The alkali metals and alkaline earth metals are representative elements; all other metals are not.

**SALT:** Generally, a salt is any compound that brings together a metal and a nonmetal. Salts are produced, along with water, in the reaction of an acid and a base.

**TRANSITION METALS:** A group of 40 elements (counting lanthanum and actinium), which are not assigned a group number in the version of the periodic table of elements known as the North American system. These are the only elements that fill the d orbital. In addition, the transition metals—unlike the representative or main-group elements—have their valence electrons on two different principal energy levels. Though the lanthanides and actinides are known as inner transition metals, they are usually treated separately.

**VALENCE ELECTRONS:** Electrons that occupy the highest principal energy level in an atom. These are the electrons involved in chemical bonding.

to make metal type. When poured into forms cut with the shapes of letters and other characters, the alloy produced symbols with clear, sharp edges.

Wood's metal is a bismuth alloy involving cadmium, tin, and lead, which melts at a temperature of 158°F (70°C). This makes it useful for automatic sprinkler systems inside a building: when a fire breaks out, it melts the Wood's metal seal, and turns on the sprinklers. Bismuth compounds are applied in cosmetics, paints, and dyes, and prior to the twentieth century, compounds of bismuth were widely used for treating sexually transmitted diseases. Today, antibiotics have largely taken their place, but bismuth still has one well-known medicinal application: in bismuth subsalicylate, better known by the brand name Pepto-Bismol.

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# ALKALI METALS

## CONCEPT

Group 1 of the periodic table of elements consists of hydrogen, and below it the six alkali metals: lithium, sodium, potassium, rubidium, cesium, and francium. The last three are extremely rare, and have little to do with everyday life; on the other hand, it is hard to spend a day without encountering at least one of the first three—particularly sodium, found in table salt. Along with potassium, sodium is an important component of the human diet, and in compounds with other substances, it has an almost endless array of uses. Lithium does not have as many applications, but to many people who have received it as a medication for bipolar disorder, it is quite literally a life-saver.

## HOW IT WORKS

### Electron Configuration of the Alkali Metals

In the essay on Families of Elements, there is a lengthy discussion concerning the relationship between electron configuration and the definition of a particular collection of elements as a "family." Here that subject will only be touched upon lightly, inasmuch as it relates to the alkali metals.

All members of Group 1 on the periodic table of elements have a valence electron configuration of $s^1$. This means that a single electron is involved in chemical bonding, and that this single electron moves through an orbital, or range of probabilities, roughly corresponding to a sphere.

Most elements bond according to what is known as the octet rule, meaning that when two or more atoms are bonded, each has (or shares) eight valence electrons. It is for this reason that the noble gases, at the opposite side of the periodic table from the alkali metals, almost never bond with other elements: they already have eight valence electrons.

The alkali metals, on the other hand, are quite likely to find "willing partners," since they each have just one valence electron. This brings up one of the reasons why hydrogen, though it is also part of Group 1, is not included as an alkali metal. First and most obviously, it is not a metal; additionally, it bonds according to what is called the duet rule, such that it shares two electrons with another element.

### Chemical and Physical Characteristics of the Alkali Metals

The term "alkali" (essentially the opposite of an acid) refers to a substance that forms the negatively charged hydroxide ion (OH-) in contact with water. On their own, however, alkali metals almost always form positive ions, or cations, with a charge of +1.

When alkali metals react with water, one hydrogen atom splits off from the water molecule to form hydrogen gas, while the other hydrogen atom joins the oxygen to form hydroxide. Where the heavier members of the alkali metal family are concerned, reactions can often be so vigorous that the result is combustion or even explosion. Alkali metals also react with oxygen to produce



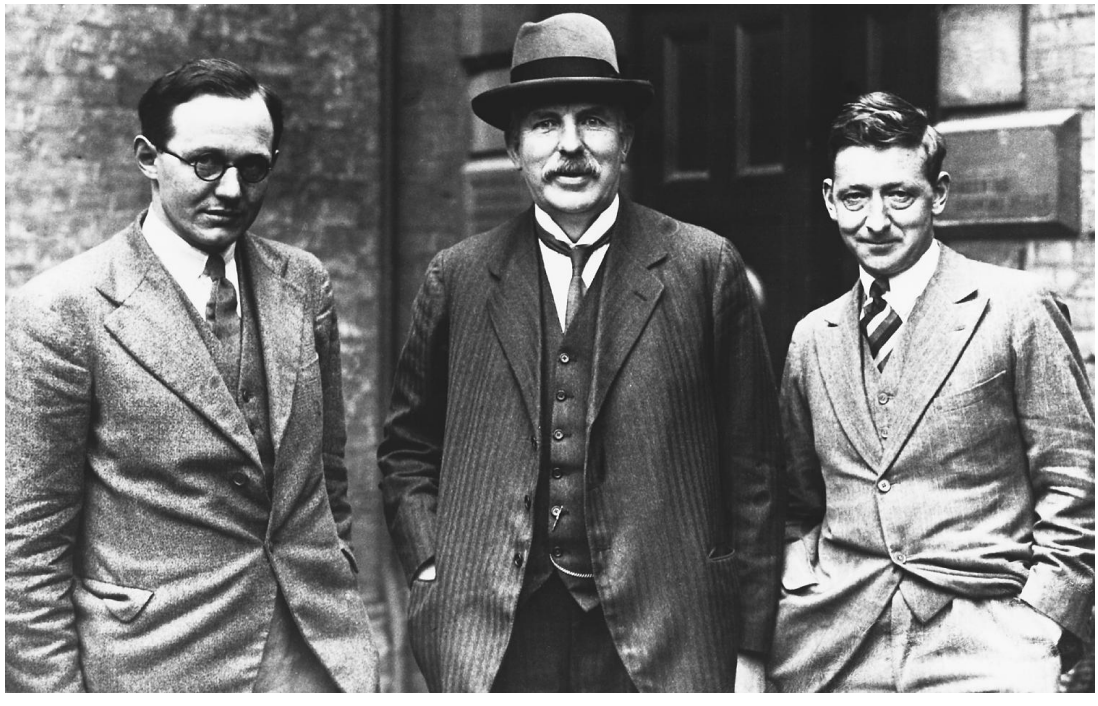

One of the uses of lithium is in batteries. The Nissan Hypermini is an electric vehicle powered by a lithium battery. *(Reuters NewMedia Inc./Corbis. Reproduced by permission.)*

either an oxide, peroxide, or superoxide, depending on the particular member of the alkali metal family involved.

Shiny and soft enough to be cut with a knife, the alkali metals are usually white (though cesium is more of a yellowish white). When placed in a flame, most of these substances produce characteristic colors: lithium, for instance, glows bright red, and sodium an intense yellow. Heated potassium produces a violet color, rubidium a dark red, and cesium a light blue. This makes it possible to identify the metals, when heated, by color—a useful trait, since they are so often inclined to be bonded with other elements.

**MELTING AND BOILING POINTS.** As one moves down the rows or periods of the periodic table, the mass of atoms increases, as does the energy each atom possesses. Yet the amount of energy required to turn a solid alkali metal into a liquid, or to vaporize a liquid alkali metal, actually decreases with higher atomic number. In other words, the higher the atomic number, the lower the boiling and melting points.

The list below lists the six alkali metals in order of atomic number, along with chemical symbol, atomic mass, melting point, and boiling point. Note that for francium, which is radioactive, the figures given are for its most stable isotope, francium-223 ($^{223}$Fr)—which has a half-life of only about 21 minutes.



One of the most striking uses of lithium occurred in 1932, with the development of the first particle accelerator. Shown here are its inventors, Ernest Walton (left), Ernest Rutherford (center), and John Cockcroft. *(Hulton-Deutsch Collection/Corbis. Reproduced by permission.)*

**Atomic Number, Mass, and Melting and Boiling Points of the Alkali Metals:**

- 3. **Lithium** (Li), 6.941; Melting Point: 356.9°F (180.5°C); Boiling Point: 2,457°F (1,347°C)
- 11. **Sodium** (Na), 22.99; Melting Point: 208°F (97.8°C); Boiling Point: 1,621.4°F (883°C)
- 19. **Potassium** (K), 39.10; Melting Point: 145.9°F (63.28°C); Boiling Point: 1,398.2°F (759°C)
- 37. **Rubidium** (Rb), 85.47; Melting Point: 102.8°F (39.31°C); Boiling Point: 1,270.4°F (688°C)
- 55. **Cesium** (Cs), 132.9; Melting Point: 83.12°F (28.4°C); Boiling Point: 1,239.8°F (671°C)
- 87. **Francium** (Fr), (223); Melting Point: 80.6°F (27°C); Boiling Point: 1,250.6°F (677°C)

### Abundance of Alkali Metals

Sodium and potassium are, respectively, the sixth and seventh most abundant elements on Earth, comprising 2.6% and 2.4% of the planet's known elemental mass. This may not seem like much, but considering the fact that just two elements—oxygen and silicon—make up about 75%, and that just 16 elements make up most of the remainder, it is an impressive share.

Lithium, on the other hand, is much less abundant, and therefore, figures for its part of Earth's known elemental mass are measured in parts per million (ppm). The total lithium in Earth's crust is about 17 ppm. Surprisingly, rubidium is more abundant, at 60 ppm; less surprisingly, cesium, with just 3 ppm, is very rare. Almost no francium is found naturally, except in very small quantities within uranium ores.

## Real-Life Applications

### Lithium

Swedish chemist Johan August Arfvedson (1792-1841) discovered lithium in 1817, and named it after the Greek word for "stone." Four years later, another scientist named W. T. Brande succeeded in isolating the highly reactive metal. Most of the lithium available on Earth's crust is bound up with aluminum and silica in minerals.

Since the time of its discovery, lithium has been used in lubricants, glass, and in alloys of

lead, aluminum, and magnesium. In glass, it acts as a strengthening agent; likewise, metal alloys that contain lithium tend to be stronger, yet less dense. In 1994, physicist Jeff Dahn of Simon Fraser University in British Columbia, Canada, developed a lithium battery. Not only was the battery cheaper to produce than the traditional variety, Dahn and his colleagues announced, but the disposal of used lithium batteries presented less danger to the environment.

One of the most striking uses of lithium occurred in 1932, when English physicist John D. Cockcroft (1897-1967) and Irish physicist Ernest Walton (1903-1995) built the first particle accelerator. By bombarding lithium atoms, they produced highly energized alpha particles. This was the first nuclear reaction brought about by the use of artificially accelerated particles—in other words, without the need for radioactive materials such as uranium-235. Cockcroft's and Walton's experiment with lithium thus proved pivotal to the later creation of the atomic bomb.

**LITHIUM IN PSYCHIATRIC TREATMENT.** The most important application of lithium, however, is in treatment for the psychiatric condition once known as manic depression, today identified as bipolar disorder. Persons suffering from bipolar disorder tend toward mood swings: during some periods the patient is giddy ("manic," or in a condition of "mania"), and during others the person is suicidal. Indeed, prior to the development of lithium as a treatment for bipolar disorder, as many as one in five patients with this condition committed suicide.

Doctors do not know exactly how lithium does what it does, but it obviously works: between 70% and 80% of patients with the bipolar condition respond well to treatment, and are able to go on with their lives in such a way that their condition is no longer outwardly evident. Lithium is also administered to patients who suffer unipolar depression and some forms of schizophrenia.

**EARLY MEDICINAL USES OF LITHIUM.** It is said that the great Greco-Roman physician Galen ( 129-c. 199) counseled patients suffering from "mania" to bathe in, and even drink the water from, alkaline springs. If so, he was nearly 2,000 years ahead of his time. Even in the 1840s, not long after lithium was discovered, the mineral—mixed with carbonate or citrate—was touted as a cure for insomnia, gout, epilepsy, diabetes, and even cancer.

None of these alleged cures proved a success; nor did a lithium chloride treatment administered in the 1940s as a salt substitute for patients on low-sodium diets. As it turned out, when not enough sodium is present, the body experiences a buildup of sodium's sister element, lithium. The result was poisoning, which in some cases proved fatal.

**CADE'S BREAKTHROUGH.** Then in 1949, Australian psychiatrist John Cade discovered the value of lithium for psychiatric treatment. He approached the problem from an entirely different angle, experimenting with uric acid, which he believed to be a cause of manic behavior. In administering the acid to guinea pigs, he added lithium salts merely to keep the uric acid soluble—and was very surprised by what he discovered. The uric acid did not make the guinea pigs manic, as he had expected; instead, they became exceedingly calm.

Cade changed the focus of his research, and tested lithium treatment on ten manic patients. Again, the results were astounding: one patient who had suffered from an acute bipolar disorder (as it is now known) for five years was released from the hospital after three months of lithium treatment, and went on to lead a healthy, normal life.

Encouraged by the changes he had seen in patients who received lithium, Cade published a report on his findings in the *Medical Journal of Australia*, but his work had little impact at the time. Nor did the idea of lithium treatment meet with an enthusiastic reception on the other side of the Pacific: in the aftermath of the failed experiments with lithium as a sodium substitute in the 1940s, stories of lithium poisoning were widespread in the United States.

**LITHIUM TODAY.** Were it not for the efforts of Danish physician Mogens Schou, lithium might never have taken hold in the medical community. During the 1950s and 1960s, Schou campaigned tirelessly for recognition of lithium as a treatment for manic-depressive illness. Finally during the 1960s, the U.S. Food and Drug Administration began conducting trials of lithium, and approved its use in 1974. Today some 200,000 Americans receive lithium treatments.

A non-addictive and non-sedating medication, lithium—as evidenced by the failed experiment in the 1940s—may still be dangerous in large quantities. It is absorbed quickly into the bloodstream and carried to all tissues in the brain and body before passing through the kidneys. Both lithium and sodium are excreted through the kidneys, and since sodium affects lithium excretion, it is necessary to maintain a proper quantity of sodium in the body. For this reason, patients on lithium are cautioned to avoid a low-salt diet.

## Sodium

Sodium compounds had been known for some time prior to 1807, when English chemist Sir Humphry Davy (1778-1829) succeeded in isolating sodium itself. The element is represented by a chemical symbol (Na), reflecting its Latin name, *natrium*. In its pure form, sodium has a bright, shiny surface, but in order to preserve this appearance, it must be stored in oil: sodium reacts quickly with oxygen, forming a white crust of sodium oxide.

Pure sodium never occurs in nature; instead, it combines readily with other substances to form compounds, many of which are among the most widely used chemicals in industry. It is also highly soluble: thus whereas sodium and potassium occur in crystal rocks at about the same ratio, sodium is about 30 times more abundant in seawater than its sister element.

**OBTAINING SODIUM CHLORIDE.** Though the extraction of sodium involves the use of a special process, the metal is plentiful in the form of sodium chloride—better known as table salt. In fact, the term salt in chemistry refers generally to any combination of a metal with a nonmetal. More specifically, salts are (along with water) the product of reactions between acids and bases.

Sodium chloride is so easy to obtain, and therefore so cheap, that most industries making other sodium compounds use it, simply separating out the chloride (as described below) before adding other elements. The United States is the world's largest producer of sodium chloride, obtained primarily from brine, a term used to describe any solution of sodium chloride in water. Brine comes from seawater, subterranean wells, and desert lakes, such as the Great Salt Lake in Utah. Another source of sodium chloride is rock salt, created underground by the evaporation of long-buried saltwater seas.

Other top sodium-chloride-producing nations include China, Germany, Great Britain, France, India, and various countries in the former Soviet Union. Salt may be cheap and plentiful for the world in general, but there are places where it is a precious commodity. One such place is the Sahara Desert, where salt caravans ply a brisk trade today, much as they have since ancient times.

**ISOLATING SODIUM.** Modern methods for the production of sodium represent an improvement in the technique Davy used in 1807, although the basic principle is the same. Though several decades passed before electricity came into widespread public use, scientists had been studying its properties for years, and Davy applied it in a process called electrolysis.

Electrolysis is the use of an electric current to produce a chemical reaction—in this case, to separate sodium from the other element or elements with which it is combined. Davy first fused or melted a sample of sodium chloride, then electrolyzed it. Using an electrode, a device that conducts electricity and is used to emit or collect electric charge, he separated the sodium chloride in such a way that liquid sodium metal collected on the cathode, or negatively charged end. Meanwhile, the gaseous chlorine was released through the anode, or the positively charged end.

The apparatus used for sodium separation today is known as the Downs cell, after its inventor, J. C. Downs. In a Downs cell, sodium chloride and calcium chloride are combined in a molten mixture in which the presence of calcium chloride lowers the melting point of the sodium chloride by more than 30%. When an electric current is passed through the mixture, sodium ions move to the cathode, where they pick up electrons to become sodium atoms. At the same time, ions of chlorine migrate to the anode, losing electrons to become chlorine atoms.

Sodium is a low-density material that floats on water, and in the Downs cell, the molten sodium rises to the top, where it is drawn off. The chlorine gas is allowed to escape through a vent at the top of the anode end of the cell, and the resulting sodium metal—that is, the elemental form of sodium—is about 99.8% pure.

**USES FOR SODIUM CHLORIDE.** As indicated earlier, sodium chloride is by far the most widely known and commonly used sodium

compound—and this in itself is a distinction, given the fact that so many sodium compounds are a part of daily life. Today people think of salt primarily as a seasoning to enhance the taste of food, but prior to the development of refrigeration, it was vital as a preservative because it kept microbes away from otherwise perishable food items.

Salt does not merely improve the taste of food; it is an essential nutrient. Sodium compounds regulate transmission of signals through the nervous system, alter the permeability of membranes, and perform a number of other life-preserving functions. On the other hand, too much salt can aggravate high blood pressure. Thus, since the 1970s and 1980s, food manufacturers have increasingly offered products low in sodium, a major selling point for health-conscious consumers.

**OTHER SODIUM COMPOUNDS.** In addition to its widespread use in consumer goods, sodium chloride is the principal source of sodium used in making other sodium compounds. These include sodium hydroxide, for manufacturing cellulose products such as film, rayon, soaps, and paper, and for refining petroleum. In its application as a cleaning solution, sodium hydroxide is known as caustic soda or lye.

Another widely used sodium compound is sodium carbonate or, soda ash, applied in glass-making, paper production, textile manufacturing, and other areas, such as the production of soaps and detergents. Sodium also can be combined with carbon to produce sodium bicarbonate, or baking soda. Sodium sulfate, sometimes known as salt cake, is used for making cardboard and kraft paper. Yet another widely used sodium compound is sodium silicate, or "water glass," used in the production of soaps, detergents, and adhesives; in water treatment; and in bleaching and sizing of textiles.

Still other sodium compounds used by industry and/or consumers include sodium borate, or borax; sodium tartrate, or sal tartar; the explosive sodium nitrate, or Chilean saltpeter; and the food additive monosodium glutamate (MSG). Perhaps ironically, there are few uses for pure metallic sodium. Once applied as an "anti-knock" additive in leaded gasoline, before those products were phased out for environmental reasons, metallic sodium is now used as a heat-exchange medium in nuclear reactors. But its widest application is in the production of the many other sodium compounds used around the world.

## Potassium

In some ways, potassium is a strange substance, as evidenced by its behavior in response to water. As everyone knows, water tends to put out a fire, and most explosives, when exposed to sufficient quantities of water, become ineffective. Potassium, on the other hand, explodes in contact with water and reacts violently with ice at temperatures as low as -148°F (-100°C). In a complete reversal of the procedures normally followed for most substances, potassium is stored in kerosene, because it might burst into flames if exposed to moist air!

Many aspects of potassium mirror those already covered with regard to sodium. The two have a number of the same applications, and in certain situations, potassium is used as a sodium substitute. Like sodium, potassium is never found alone in nature; instead, it comes primarily from sylvinite and carnalite, two ores containing potassium chloride. Also, like sodium, potassium was first isolated in 1807 by Davy, using the process of electrolysis described above. A few years later, a German chemist dubbed the newly isolated element "kalium," apparently a derivation of the Arabic *qali*, for "alkali"; hence the use of K as the chemical symbol for potassium.

**USES FOR POTASSIUM.** Potassium has another similarity with sodium; although it was not isolated until the early nineteenth century, its compounds have been in use for many centuries. The Romans, for instance, used potassium carbonate, or potash, obtained from the ashes of burned wood, to make soap. During the Middle Ages, the Chinese applied a form of saltpeter, potassium nitrate, in making gunpowder. And in colonial America, potash went into the production of soap, glass, and other products.

The production of just one ton of potash required the burning of several acres' worth of trees—a wasteful practice in more ways than one. Though there was no environmentalist movement in those days, financial concerns never go out of style. In order to save the money lost by using up vast acres of timber, American industry in the nineteenth century sought another means of making potash. The many similarities between



In the Sahara Desert, salt caravans ply a brisk trade today, much as they have since ancient times. Here, traders in Mali load a camel for a salt caravan. *(Nik Wheeler/Corbis. Reproduced by permission.)*

sodium and potassium provided a key, and the substitution of sodium carbonate for potassium carbonate saved millions of trees.

In 1847, German chemist Justus von Liebig (1803-1873) discovered potassium in living tissues. As a result, scientists became aware of the role this alkali metal plays in sustaining life: indeed, potassium is present in virtually all living cells. In the human body, potassium—which accounts for only 0.4% of the body's mass—is

## KEY TERMS

**ALKALI METALS:** The elements in Group 1 of the periodic table of elements, with the exception of hydrogen. The alkali metals, which include lithium, sodium, potassium, rubidium, cesium, and francium, all have one valence electron in the $s^1$ orbital, and are highly reactive.

**ANODE:** An electrode at the positively charged end of a supply of electric current.

**BRINE:** A term used to describe any solution of sodium chloride in water.

**CATHODE:** An electrode at the negatively charged end of a supply of electric current.

**CATION:** The positive ion that results when an atom loses one or more electrons. All of the alkali metals tend to form +1 cations (pronounced KAT-ie-un).

**ELECTRODE:** A structure, often a metal plate or grid, that conducts electricity, and which is used to emit or collect electric charge.

**ELECTROLYSIS:** The use of an electric current to cause a chemical reaction.

**HALF-LIFE:** The length of time it takes a substance to diminish to one-half its initial amount.

**ION:** An atom or group of atoms 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. Isotopes may be either stable or unstable—that is, radioactive. Such is the case with francium, a radioactive member of the alkali metals family.

**ORBITAL:** A pattern of probabilities regarding the position of an electron for an atom in a particular energy state. The six alkali metals all have valence electrons in an $s^1$ orbital, which describes a more or less spherical shape.

**PERIODIC TABLE OF ELEMENTS:** A chart that shows the elements arranged in order of atomic number. Vertical columns within the periodic table indicate groups or "families" of elements with similar chemical characteristics; the alkali metals occupy Group 1.

**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. "Decay" in this sense does not mean "rot"; instead, radioactive isotopes continue changing into other isotopes until they become stable.

**SALT:** A compound formed, along with water, by the reaction of an acid and a base. Generally, salts are any compounds that bring together a metal and a nonmetal.

**VALENCE ELECTRONS:** Electrons that occupy the highest energy levels in an atom, and which are involved in chemical bonding. The alkali metals all have one valence electron, in the $s^1$ orbital.

essential to the functioning of muscles. In larger quantities, however, it can be dangerous, causing a state of permanent relaxation known as potassium inhibition.

Since plants depend on potassium for growth, it was only logical that potassium, in the form of potassium chloride, was eventually applied as a fertilizer. This, at least, distinguishes it from its sister element: sodium, or sodium chloride, which can kill plants if administered to the soil in large enough quantities.

Another application of potassium is in the area pioneered by the Chinese about 800 years ago: the manufacture of fireworks and gunpowder from potassium nitrate. Like ammonium nitrate, made infamous by its use in the 1993 World Trade Center bombing and the Oklahoma City bombing in 1995, potassium nitrate doubles as a fertilizer.

## Rubidium, Cesium, and Francium

The three heaviest alkali metals are hardly household names, though one of them, cesium, does have several applications in industry. Rubidium and cesium, discovered in 1860 by German chemist R. W. Bunsen (1811-1899) and German physicist Gustav Robert Kirchhoff (1824-1887), were the first elements ever found using a spectroscope. Matter emits electromagnetic radiation along various spectral lines, which can be recorded using a spectroscope and then analyzed to discern the particular "fingerprint" of the substance in question.

When Bunsen and Kirchhoff saw the bluish spectral lines emitted by one of the two elements, they named it cesium, after a Latin word meaning "sky blue." Cesium, which is very rare, appears primarily in compounds such as pollucite. It is used today in photoelectric cells, military infrared lamps, radio tubes, and video equipment. During the 1940s, American physicist Norman F. Ramsey, Jr. (1915-) built a highly accurate atomic clock based on the natural frequencies of cesium atoms.

Rubidium, by contrast, has far fewer applications, and those are primarily in areas of scientific research. On Earth it is found in pollucite, lepidolite, and carnallite. It is considerably more abundant than cesium, and vastly more so than francium. Indeed, it is estimated that if all the francium in Earth's crust were combined, it would have a mass of about 25 grams.

Francium was discovered in 1939 by French physicist Marguerite Perey (1909-1975), student of the famous French-Polish physicist and chemist Marie Curie (1867-1934). For about four decades, scientists had been searching for the mysterious Element 87, and while studying the decay products of an actinium isotope, actinium-227, Perey discovered that one out of 100 such atoms decayed to form the undiscovered element. She named it francium, after her homeland. Though the discovery of francium solved a mystery, the element has no known uses outside of its applications in research.

## WHERE TO LEARN MORE

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# ALKALINE EARTH METALS

## CONCEPT

The six alkaline earth metals—beryllium, magnesium, calcium, strontium, barium, and radium—comprise Group 2 on the periodic table of elements. This puts them beside the alkali metals in Group 1, and as their names suggest, the two families share a number of characteristics, most notably their high reactivity. Also, like the alkali metals, or indeed any other family on the periodic table, not all members of the alkali metal family are created equally in terms of their abundance on Earth or their usefulness to human life. Magnesium and calcium have a number of uses, ranging from building and other structural applications to dietary supplements. In fact, both are significant components in the metabolism of living things—including the human body. Barium and beryllium have numerous specialized applications in areas from jewelry to medicine, while strontium is primarily used in fireworks. Radium, on the other hand, is rarely used outside of laboratories, in large part because its radioactive qualities pose a hazard to human life.

## HOW IT WORKS

### Defining a Family

The expression "families of elements" refers to groups of elements on the periodic table that share certain characteristics. These include (in addition to the alkaline earth metals and the alkali metals) the transition metals, halogens, noble gases, lanthanides, and actinides. (All of these are covered in separate essays within this book.) In addition, there are several larger categories with regard to shared traits that often cross family lines; thus all elements are classified either as metals, metalloids, and nonmetals. (These are also discussed in separate essays, which include reference to "orphans," or elements that do not belong to one of the families mentioned above.)

These groupings, both in terms of family and the broader divisions, relate both to external, observable characteristics, as well as to behaviors on the part of electrons in the elements' atomic structures. For instance, metals, which comprise the vast majority of elements on the periodic table, tend to be shiny, hard, and malleable (that is, they can bend without breaking.) Many of them melt at fairly high temperatures, and virtually all of them vaporize (become gases) at high temperatures. Metals also form ionic bonds, the tightest form of chemical bonding.

**ELECTRON CONFIGURATIONS OF THE ALKALINE EARTH METALS.** Where families are concerned, there are certain observable properties that led chemists in the past to group the alkaline earth metals together. These properties will be discussed with regard to the alkaline earth metals, but another point should be stressed in relation to the division of elements into families. With the advances in understanding that followed the discovery of the electron in 1897, along with the development of quantum theory in the early twentieth century, chemists developed a more fundamental definition of family in terms of electron configuration.

As noted, the alkaline earth metal family occupies the second group, or column, in the periodic table. All elements in a particular group, regardless of their apparent differences, have a common pattern in the configuration of their




During World War II, magnesium was heavily used in aircraft components. In this 1941 photo, workers pour molten magnesium into a cast at the Wright Aeronautical Corporation. *(Bettmann/Corbis. Reproduced by permission.)*

valence electrons—the electrons at the "outside" of the atom, involved in chemical bonding. (By contrast, the core electrons, which occupy lower regions of energy within the atom, play no role in the bonding of elements.)

All members of the alkaline earth metal family have a valence electron configuration of $s^2$. This means that two electrons are involved in chemical bonding, and that these electrons move through an orbital, or range of probabilities, roughly corresponding to a sphere. The *s* orbital pattern corresponds to the first of several sublevels within a principal energy level.

Whatever the number of the principal energy level which corresponds to the period, or row, on the periodic table the atom has the same number of sublevels. Thus beryllium, on Period 2, has two principal energy levels, and its valence electrons are in sublevel $2s^2$. At the other end of the group is radium, on Period 7. Though radium is far more complex than beryllium, with seven energy levels instead of two, nonetheless it has the same valence electron configuration, only on a higher energy level: $7s^2$.

**HELIUM AND THE ALKALINE EARTH METALS.** If one studies the valence electron configurations of elements on the periodic table, one notices an amazing symmetry and order. All members of a group, though their principal energy levels differ, share characteristics in

their valence shell patterns. Furthermore, for the eight groups numbered in the North American version of the periodic table, the group number corresponds to the number of valence electrons.

There is only one exception: helium, with a valence electron configuration of $1s^2$, is normally placed in Group 8 with the noble gases. Based on that $s^2$ configuration, it might seem logical to place helium atop beryllium in the alkaline earth metals family; but there are several reasons why this is not done. First of all, helium is obviously not a metal. More importantly, helium behaves in a manner quite different from that of the alkaline earth metals.

Whereas helium, like the rest of the noble gases, is highly resistant to chemical reactions and bonding, alkaline earth metals are known for their high reactivity—that is, a tendency for bonds between atoms or molecules to be made or broken so that materials are transformed. (A similar relationship exists in Group 1, which includes hydrogen and the alkali metals. All have the same valence configuration, but hydrogen is never included as a member of the alkali metals family.)

## Characteristics of the Alkaline Earth Metals

Like the alkali metals, the alkaline earth metals have the properties of a base, as opposed to an acid. The alkaline earth metals are shiny, and most are white or silvery in color. Like their "cousins" in the alkali metal family, they glow with characteristic colors when heated. Calcium glows orange, strontium a very bright red, and barium an apple green. Physically they are soft, though not as soft as the alkali metals, many of which can be cut with a knife.

Yet another similarity the alkaline earth metals have with the alkali metals is the fact that four of the them—magnesium, calcium, strontium, and barium—were either identified or isolated in the first decade of the nineteenth century by English chemist Sir Humphry Davy (1778-1829). Around the same time, Davy also isolated sodium and potassium from the alkali metal family.

**REACTIVITY.** The alkaline earth metals are less reactive than the alkali metals, but like the alkali metals they are much more reactive than most elements. Again like their "cousins," they react with water to produce hydrogen gas and the metal hydroxide, though their reactions are less pronounced than those of the alkali metals. Magnesium metal in its pure form is combustible, and when exposed to air, it burns with an intense white light, combining with the oxygen to produce magnesium oxide. Likewise calcium, strontium, and barium react with oxygen to form oxides.

Due to their high levels of reactivity, the alkaline earth metals rarely appear by themselves in nature; rather, they are typically found with other elements in compound form, often as carbonates or sulfates. This, again, is another similarity with the alkali metals. But whereas the alkali metals tend to form 1+ cations (positively charged atoms), the alkaline earth metals form 2+ cations—that is, cations with a positive charge of 2.

**BOILING AND MELTING POINTS.** One way that the alkaline earth metals are distinguished from the alkali metals is with regard to melting and boiling points—those temperatures, respectively, at which a solid metal turns into a liquid, and a liquid metal into a vapor. For the alkali metals, the temperatures of the boiling and melting points decrease with an increase in atomic number. The pattern is not so clear, however, for the alkaline earth metals.

The highest melting and boiling points are for beryllium, which indeed has the lowest atomic number. It melts at 2,348.6°F (1,287°C), and boils at 4,789.8°F (2,471°C). These figures are much higher than for lithium, the alkali metal on the same period as beryllium, which melts at 356.9°F (180.5°C) and boils at 2,457°F (1,347°C).

Magnesium, the second alkali earth metal, melts at 1,202°F (650°C), and boils at 1,994°F (1,090°C)—significantly lower figures than for beryllium. However, the melting and boiling points are higher for calcium, third of the alkaline earth metals, with figures of 1,547.6°F (842°C) and 2,703.2°F (1,484°C) respectively. Melting and boiling temperatures steadily decrease as energy levels rise through strontium, barium, and radium, yet these temperatures are never lower than for magnesium.

**ABUNDANCE.** Of the alkaline earth metals, calcium is the most abundant. It ranks fifth among elements in Earth's crust, accounting for 3.39% of the elemental mass. It is also fifth most abundant in the human body, with a share



Many alkaline earth metals are used in the production of fireworks. *(Bill Ross/Corbis. Reproduced by permission.)*

of 1.4%. Magnesium, which makes up 1.93% of Earth's crust, is the eighth most abundant element on Earth. It ranks seventh in the human body, accounting for 0.50% of the body's mass.

Barium ranks seventeenth among elements in Earth's crust, though it accounts for only 0.04% of the elemental mass. Neither it nor the other three alkali metals appear in the body in significant quantities: indeed, barium and beryllium are poisonous, and radium is so radioactive that exposure to it can be extremely harmful.

Within Earth's crust, strontium is present in quantities of 360 parts per million (ppm), which in fact is rather abundant compared to a number of elements. In the ocean, its presence is about 8 ppm. By contrast, the abundance of beryllium in Earth's crust is measured in parts per billion (ppb), and is estimated at 1,900 ppb. Vastly more rare is radium, which accounts for just 0.6 parts per trillion of Earth's crust—a fact that made its isolation by French-Polish physicist and chemist Marie Curie (1867-1934) all the more impressive.

## REAL-LIFE APPLICATIONS

### BERYLLIUM

In the eighteenth century, French mineralogist René Just-Haüy (1743-1822) had observed that both emeralds and the mineral beryl had similar properties. French chemist Louis-Nicolas Vauquelin (1763-1829) in 1798 identified the element they had in common: beryllium (Be), which has an atomic number of 4 and an atomic mass of 9.01 amu. Some three decades passed before German chemist Friedrich Wöhler (1800-1882) and French chemist Antoine Bussy (1794-1882), working independently, succeeded in isolating the element.

Beryllium is found primarily in emeralds and aquamarines, both precious stones that are forms of the beryllium alluminosilicate compound beryl. Though it is toxic to humans, beryllium nonetheless has an application in the health-care industry: because it lets through more x rays than does glass, beryllium is often used in x-ray tubes.

Metal alloys that contain about 2% beryllium tend to be particularly strong, resistant to wear, and stable at high temperatures. Copper-beryllium alloys, for instance, are applied in hand tools for industries that use flammable solvents, since tools made of these alloys do not cause sparks when struck against one another. Alloys of beryllium and nickel are applied for specialized electrical connections, as well as for high-temperature uses.

### MAGNESIUM

English botanist and physician Nehemiah Grew (1641-1712) in 1695 discovered magnesium sulfate in the springs near the English town of Epsom, Surrey. This compound, called "Epsom salts" ever since, has long been noted for its medicinal value. Epsom salts are used for treating eclampsia, a condition that causes seizures in pregnant women. The compound is also a powerful laxative, and is sometimes used to rid the body of poisons—such as magnesium's sister element, barium.

For some time, scientists confused the oxide compound magnesia with lime or calcium carbonate, which actually involves another alkaline earth metal. In 1754, Scottish chemist and physicist Joseph Black (1728-1799) wrote "Experiments Upon Magnesia, Alba, Quick-Lime, and Some Other Alkaline Substances," an important work in which he distinguished between magnesia and lime. Davy in 1808 declared magnesia the oxide of a new element, which he dubbed magnesium, but some 20 years passed before Bussy succeeded in isolating the element.

Magnesium (Mg) has an atomic number of 12, and an atomic mass of 24.31 amu. It is found primarily in minerals such as dolomite and magnesite, both of which are carbonates; and in carnallite, a chloride. Magnesium silicates include asbestos, soapstone or talc, and mica. Not all forms of asbestos contain magnesium, but the fact that many do only serves to show the ways that chemical reactions can change the properties an element possesses in isolation.

**AN IMPORTANT COMPONENT OF HEALTH.** Whereas magnesium is flammable, asbestos was once used in large quantities as a flame retardant. And whereas asbestos has been largely removed from public buildings throughout the United States due to reports linking asbestos exposure with cancer, magnesium is an important component in the health of living organisms. It plays a critical role in chlorophyll, the green pigment in plants that captures energy from sunlight, and for this reason, it is also used in fertilizers.

In the human body, magnesium ions (charged atoms) aid in the digestive process, and many people take mineral supplements containing magnesium, sometimes in combination with calcium. There is also its use as a laxative, already mentioned. Epsom salts, as befits their base or alkaline quality, are exceedingly bitter—the kind of substance a person only ingests under conditions of the most dire necessity. On the other hand, milk of magnesia is a laxative with a far less unpleasant taste.

**MAGNESIUM GOES TO WAR.** It is a hallmark of magnesium's chemical versatility that the same element, so important in preserving life, has also been widely used in warfare. Just before World War I, Germany was a leading manufacturer of magnesium, thanks in large part to a method of electrolysis developed by German chemist R. W. Bunsen (1811-1899). When the United States went to war against Germany, American companies began producing magnesium in large quantities.

Bunsen had discovered that powdered magnesium burns with a brilliant white flame, and in the war, magnesium was used in flares, tracer bullets, and incendiary bombs, which ignite and burn upon impact. The bright light produced by burning magnesium has also led to a number of peacetime applications—for instance, in fireworks, and for flashes used in photography.

Magnesium saw service in another world war. By the time Nazi tanks rolled into Poland in 1939, the German military-industrial complex had begun using the metal for building aircraft and other forms of military equipment. America once again put its own war-production machine into operation, dramatically increasing magnesium output to a peak of nearly 184,000 tons (166,924,800 kg) in 1943.

**STRUCTURAL APPLICATIONS.** Magnesium's principal use in World War I was for its incendiary qualities, but in World War II it was primarily used as a structural metal. It is lightweight, but stronger per unit of mass than any other common structural metal. As a metal for building machines and other equipment, magnesium ranks in popularity only behind iron and aluminum (which is about 50% more dense than magnesium).

The automobile industry is one area of manufacturing particularly interested in magnesium's structural qualities. On both sides of the Atlantic, automakers are using or testing vehicle parts made of alloys of magnesium and other metals, primarily aluminum. Magnesium is easily cast into complex structures, which could mean a reduction in the number of parts needed for building a car—and hence a streamlining of the assembly process.

Among the types of sports equipment employing magnesium alloys are baseball catchers' masks, skis, racecars, and even horseshoes. Various brands of ladders, portable tools, electronic equipment, binoculars, cameras, furniture, and luggage also use parts made of this lightweight, durable metal.

## Calcium

Davy isolated calcium (Ca) by means of electrolysis in 1808. The element, whose name is derived from the Latin *calx,* or "lime," has an atomic number of 20, and an atomic mass of 40.08. The principal sources of calcium are limestone and dolomite, both of which are carbonates, as well as the sulfate gypsum.

In the form of limestone and gypsum, calcium has been used as a building material since ancient times, and continues to find application in that area. Lime is combined with clay to make cement, and cement is combined with sand and water to make mortar. In addition, when mixed with sand, gravel, and water, cement makes concrete. Marble—once used to build palaces and today applied primarily for decorative touches—also contains calcium.

The steel, glass, paper, and metallurgical industries use slaked lime (calcium hydroxide) and quicklime, or calcium oxide. It helps remove impurities from steel, and pollutants from smokestacks, while calcium carbonate in paper provides smoothness and opacity to the finished product. When calcium carbide ($CaC_2$) is added to water, it produces the highly flammable gas acetylene ($C_2H_2$), used in welding torches. In various compounds, calcium is used as a bleach; a material in the production of fertilizers; and as a substitute for salt as a melting agent on icy roads.

The food, cosmetic, and pharmaceutical industries use calcium in antacids, toothpaste, chewing gum, and vitamins. To an even greater extent than magnesium, calcium is important to living things, and is present in leaves, bone, teeth, shells, and coral. In the human body, it helps in the clotting of blood, the contraction of muscles, and the regulation of the heartbeat. Found in green vegetables and dairy products, calcium (along with calcium supplements) is recommended for the prevention of osteoporosis. The latter, a condition involving a loss of bone density, affects elderly women in particular, and causes bones to become brittle and break easily.

## Strontium

Irish chemist and physician Adair Crawford (1748-1795) and Scottish chemist and surgeon William Cumberland Cruikshank (1790-1800) in 1790 discovered what Crawford called "a new species of earth" near Strontian in Scotland. A year later, English chemist Thomas Charles Hope (1766-1844) began studying the ore found by Crawford and Cruikshank, which they had dubbed strontia.

In reports produced during 1792 and 1793, Hope explained that strontia could be distinguished from lime or calcium hydroxide on the



In this 1960 photo, a mother tests her son's milk for signs of radioactivity, the result of nuclear weapons testing during the 1950s that involved the radioactive isotope strontium-90. The isotope fell to earth in a fine powder, where it coated the grass, was ingested by cows, and eventually wound up in the milk they produced. *(Bettmann/Corbis. Reproduced by permission.)*

one hand, and baryta or barium hydroxide on the other, by virtue of its response to flame tests. Whereas calcium produced a red flame and barium a green one, strontia glowed a brilliant red easily distinguished from the darker red of calcium.

Once again, it was Davy who isolated the new element, using electrolysis, in 1808. Subsequently dubbed strontium (Sr), its atomic number is 38, and its atomic mass 87.62. Silvery white, it oxidizes rapidly in air, forming a pale yellow oxide crust on any freshly cut surface.

Though it has properties similar to those of calcium, the comparative rarity of strontium and the expense involved in extracting it offer no economic incentives for using it in place of its much more abundant sister element. Nonetheless, strontium does have a few uses, primarily because of its brilliant crimson flame. Therefore it is applied in the making of fireworks, signal flares, and tracer bullets—that is, rounds that emit a light as they fly through the air.

One of the more controversial "applications" of strontium involved the radioactive isotope strontium-90, a by-product of nuclear weapons testing in the atmosphere from the late 1940s onward. The isotope fell to earth in a fine powder, coated the grass, was ingested by cows, and eventually 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.

## Barium

Aspects of barium's history are similar to those of other alkaline earth metals. During the eighteenth century, chemists were convinced that barium oxide and calcium oxide constituted the same substance, but in 1774, Swedish chemist Carl Wilhelm Scheele (1742-1786) demonstrated that barium oxide was a distinct compound. Davy isolated the element, as he did two other alkaline earth metals, by means of electrolysis, in 1808.

Barium (Ba) has an atomic mass of 137.27 and an atomic number of 56. It appears primarily in ores of barite, a sulfate, and witherite, a carbonate. Barium sulfate is used as a white pigment in paints, while barium carbonate is applied in the production of optical glass, ceramics, glazed

## KEY TERMS

**ALKALINE EARTH METALS:** Group 2 on the periodic table of elements, with valence electron configurations of $ns^2$. The six alkaline earth metals, all of which are highly reactive chemically, are beryllium, magnesium, calcium, strontium, barium, and radium.

**ALKALI METALS:** The elements in Group 1 of the periodic table of elements, with the exception of hydrogen. The alkali metals all have one valence electron in the $s^1$ orbital, and are highly reactive.

**CATION:** The positive ion that results when an atom loses one or more electrons. All of the alkaline earth metals tend to form 2+ cations (pronounced KAT-ie-unz).

**ELECTROLYSIS:** The use of an electric current to cause a chemical reaction.

**ION:** An atom or group of atoms 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. Isotopes may be either stable or unstable—that is, radioactive. Such is the case with the isotopes of radium, a radioactive member of the alkaline earth metals family.

**ORBITAL:** A pattern of probabilities regarding the position of an electron for an atom in a particular energy state. The six alkaline earth metals all have valence electrons in an $s^2$ orbital, which describes a more or less spherical shape.

**PERIODS:** Rows of the periodic table of elements. These represent successive prin-

pottery, and specialty glassware. One of its most important uses is as a drill-bit lubricant—known as a "mud" or slurry—for oil drilling. Like a number of its sister elements, barium (in the form of barium nitrate) is used in fireworks and flares. Motor oil detergents for keeping engines clean use barium oxide and barium hydroxide.

Beryllium is not the only alkaline earth metal used in making x rays, nor is magnesium the only member of the family applied as a laxative. Barium is used in enemas, and barium sulfate is used to coat the inner lining of the intestines to allow a doctor to examine a patient's digestive system. (Though barium is poisonous, in the form of barium sulfate it is safe for ingestion because the compound does not dissolve in water or other bodily fluids.) Prior to receiving x rays, a patient may be instructed to drink a chalky barium sulfate liquid, which absorbs a great deal of the radiation emitted by the x-ray machine. This adds contrast to the black-and-white x-ray photo, enabling the doctor to make a more informed diagnosis.

### Radium

Today radium (Ra; atomic number 88; atomic mass 226 amu) has few uses outside of research; nonetheless, the story of its discovery by Marie Curie and her husband Pierre (1859-1906), a French physicist, is a compelling chapter not only in the history of chemistry, but of human endeavor in general. Inspired by the discovery of uranium's radioactive properties by French physicist Henri Becquerel (1852-1908), Marie Curie became intrigued with the subject of radioactivity, on which she wrote her doctoral dissertation. Setting out to find other radioactive elements, she and Pierre refined a large quantity of pitchblende, an ore commonly found in uranium mines. Within a year, they had discovered

## KEY TERMS CONTINUED

cipal energy levels in the atoms of the elements involved.

**PRINCIPAL ENERGY LEVEL:** A value indicating the distance that an electron may move away from the nucleus of an atom. This is designated by a whole-number integer, beginning with 1 and moving upward. The higher the principal energy level, the greater the energy in the atom, and the more complex the pattern of orbitals.

**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. "Decay" in this sense does not mean "rot"; instead, radioactive isotopes continue changing into other isotopes until they become stable.

**REACTIVITY:** The tendency for bonds between atoms or molecules to be made or broken in such a way that materials are transformed.

**SALT:** Generally speaking, a compound that brings together a metal and a nonmetal. More specifically, salts (along with water) are the product of a reaction between an acid and a base.

**SHELL:** A group of electrons within the same principal energy level.

**SUBLEVEL:** A region within the principal energy level occupied by electrons in an atom. Whatever the number *n* of the principal energy level, there are *n* sublevels. At each principal energy level, the first sublevel to be filled is the one corresponding to the *s* orbital pattern—where the alkaline earth metals all have their valence electrons.

**VALENCE ELECTRONS:** Electrons that occupy the highest energy levels in an atom, and which are involved in chemical bonding.

the element polonium, but were convinced that another radioactive ingredient was present—though in much smaller amounts—in pitchblende.

The Curies spent most of their savings to purchase a ton of ore, and began working to extract enough of the hypothesized Element 88 for a usable sample—0.35 oz (1 g). Laboring virtually without ceasing for four years, the Curies—by then weary and in financial difficulties—finally produced the necessary quantity of radium. Their fortunes were about to improve: in 1903 they shared the Nobel Prize in physics with Becquerel, and in 1911, Marie received a second Nobel, this one in chemistry, for her discoveries of polonium and radium. She is the only individual in history to win Nobels in two different scientific categories.

Because the Curies failed to patent their process, however, they received no profits from the many "radium centers" that soon sprung up, touting the newly discovered element as a cure for cancer. In fact, as it turned out, the hazards associated with this highly radioactive substance outweighed any benefits. Thus radium, which at one point was used in luminous paint and on watch dials, was phased out of use. Marie Curie's death from leukemia in 1934 resulted from her prolonged exposure to radiation from radium and other elements.

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# TRANSITION METALS

## CONCEPT

By far the largest family of elements is the one known as the transition metals, sometimes called transition elements. These occupy the "dip" in the periodic table between the "tall" sets of columns or groups on either side. Consisting of 10 columns and four rows or periods, the transition metals are usually numbered at 40. With the inclusion of the two rows of transition metals in the lanthanide and actinide series respectively, however, they account for 68 elements—considerably more than half of the periodic table. The transition metals include some of the most widely known and commonly used elements, such as iron—which, along with fellow transition metals nickel and cobalt, is one of only three elements known to produce a magnetic field. Likewise, zinc, copper, and mercury are household words, while cadmium, tungsten, chromium, manganese, and titanium are at least familiar. Other transition metals, such as rhenium or hafnium, are virtually unknown to anyone who is not scientifically trained. The transition metals include the very newest elements, created in laboratories, and some of the oldest, known since the early days of civilization. Among these is gold, which, along with platinum and silver, is one of several precious metals in this varied family.

## HOW IT WORKS

### Two Numbering Systems for the Periodic Table

The periodic table of the elements, developed in 1869 by Russian chemist Dmitri Ivanovitch Mendeleev (1834-1907), is discussed in several places within this volume. Within the table, elements are arranged in columns, or groups, as well as in periods, or rows.

As discussed in the Periodic Table of Elements essay, two basic versions of the chart, differing primarily in their method of number groups, are in use today. The North American system numbers only eight groups—corresponding to the representative or main-group elements—leaving the 10 columns representing the transition metals unnumbered. On the other hand, the IUPAC system, approved by the International Union of Pure and Applied Chemistry (IUPAC), numbers all 18 columns. Both versions of the periodic table show seven periods.

In general, this book applies the North American system, in part because it is the version used in most American classrooms. Additionally, the North American system relates group number to the number of valence electrons in the outer shell of the atom for the element represented. Hence the number of valence electrons (a subject discussed below as it relates to the transition metals) for Group 8 is also eight. Yet where the transition metals are concerned, the North American system is less convenient than the IUPAC system.

**ATTEMPTS TO ADJUST THE NORTH AMERICAN SYSTEM.** In addressing the transition metals, there is no easy way to apply the North American system's correspondence between the number of valence electrons and the group number. Some versions of the North American system do, however, make an attempt. These equate the number of valence electrons in the transition metals to a group number, and distinguish these by adding a letter "B."




Several precious metals, including gold, are among the transition metals. *(Charles O'Rear/Corbis. Reproduced by permission.)*

Thus the noble gases are placed in Group 8A or VIIIA because they are a main-group family with eight valence electrons, whereas the transition metal column beginning with iron (Group 8 in the IUPAC system) is designated 8B or VIIIB. But this adjustment to the North American system only makes things more cumbersome, because Group VIIIB also includes two other columns—ones with nine and 10 valence electrons respectively.

**Value of the IUPAC system.** Obviously, then, the North American system—while it is useful in other ways, and as noted, is applied elsewhere in this book—is not as practical for discussing the transition metals. Of course, one could simply dispense with the term "group" altogether, and simply refer to the columns on the periodic table as columns. To do so, however, is to treat the table simply as a chart, rather than as a marvelously ordered means of organizing the elements.

It makes much more sense to apply the IUPAC system and to treat the transition metals as belonging to groups 3 through 12. This is particularly useful in this context, because those group numbers do correspond to the numbers of valence electrons. Scandium, in group 3 (henceforth all group numbers refer to the IUPAC version), has three valence electrons; likewise zinc, in Group 12, has 12. Neither the IUPAC nor the North American system provide group numbers for the lanthanides and actinides, known collectively as the inner transition metals.

**The transition metals by IUPAC group number.** Here, then, is the list of the transition metals by group number, as designated in the IUPAC system. Under each group heading are listed the four elements in that group, along with the atomic number, chemical symbol, and atomic mass figures for each, in atomic mass units.

Note that, because the fourth member in each group is radioactive and sometimes exists for only a few minutes or even seconds, mass figures are given merely for the most stable isotope. In addition, the last elements in groups 8, 9, and 10, as of 2001, had not received official names. For reasons that will be explained below, lanthanum and actinium, though included here, are discussed in other essays.

Group 1

- 21. Scandium (Sc): 44.9559
- 39. Yttrium (Y): 88.9059
- 57. Lanthanum (La): 138.9055
- 89. Actinium (Ac): 227.0278

Group 2

- 22. Titanium (Ti): 47.9
- 40. Zirconium (Zr): 91.22
- 72. Hafnium (Hf): 178.49
- 104. Rutherfordium (Rf): 261

Group 3

- 23. Vanadium (V): 50.9415
- 41. Niobium (Nb): 92.9064
- 73. Tantalum (Ta): 180.9479
- 105. Dubnium (Db): 262

Group 4

- 24. Chromium (Cr): 51.996
- 42. Molybdenum (Mo): 95.95
- 74. Tungsten (W): 183.85
- 106. Seaborgium (Sg): 263

Group 5

- 25. Manganese (Mn): 54.938
- 43. Technetium (Tc): 98
- 75. Rhenium (Re): 186.207
- 107. Bohrium (Bh): 262

Group 6

- 26. Iron (Fe): 55.847
- 44. Ruthenium (Ru): 101.07
- 76. Osmium (Os): 190.2
- 108. Hassium (Hs): 265

Group 7

- 27. Cobalt (Co): 58.9332
- 45. Rhodium (Rh): 102.9055
- 77. Iridium (Ir): 192.22
- 109. Meitnerium (Mt): 266

Group 8

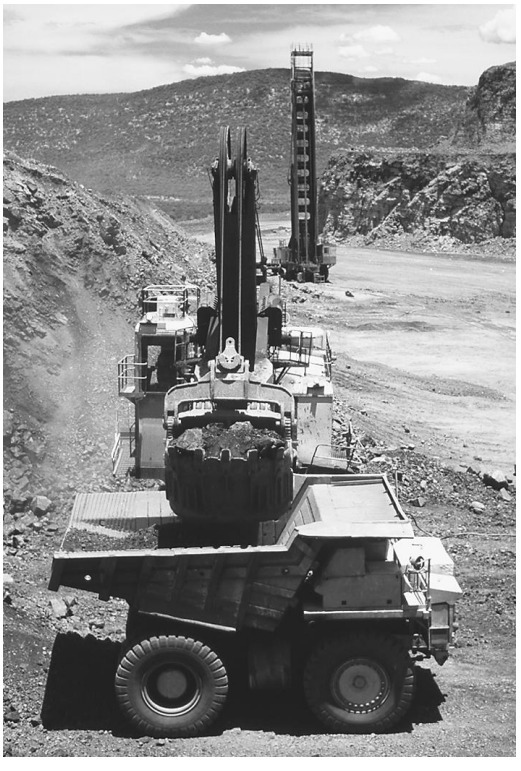
- 28. Nickel (Ni): 58.7
- 46. Palladium (Pd): 106.4
- 78. Platinum (Pt): 195.09
- 110. Ununnilium (Uun): 271

Group 9

- 29. Copper (Cu): 63.546
- 47. Silver (Ag): 107.868
- 79. Gold (Au): 196.9665
- 111. Unununium (Uuu): 272

Group 10

- 30. Zinc (Zn): 65.38
- 48. Cadmium (Cd): 112.41
- 80. Mercury (Hg): 200.59
- 112. Ununbium (Uub): 277



AN IRON ORE MINE IN SOUTH AFRICA. IRON IS THE FOURTH MOST ABUNDANT ELEMENT ON EARTH, ACCOUNTING FOR 4.71% OF THE ELEMENTAL MASS IN THE PLANET'S CRUST. *(Charles O'Rear/Corbis. Reproduced by permission.)*

## ELECTRON CONFIGURATIONS AND THE PERIODIC TABLE

We can now begin to explain why transition metals are distinguished from other elements, and why the inner transition metals are further separated from the transition metals. This distinction relates not to period (row), but to group (column)—which, in turn, is defined by the configuration of valence electrons, or the electrons that are involved in chemical bonding. Valence electrons occupy the highest energy level, or shell, of the atom—which might be thought of as the orbit farthest from the nucleus. However, the term "orbit" is misleading when applied to the ways that an electron moves.

Electrons do not move around the nucleus of an atom in regular orbits, like planets around the Sun; rather, their paths can only be loosely defined in terms of orbitals, a pattern of probabilities indicating the regions that an electron may occupy. The shape or pattern of orbitals is determined by the principal energy level of the




The American five-cent coin, called a "nickel," is actually an alloy of nickel and copper. *(Layne Kennedy/Corbis. Reproduced by permission.)*

atom, which indicates a distance that an electron may move away from the nucleus.

Principal energy level defines period: elements in Period 4, for instance, all have their valence electrons at principal energy level 4. The higher the number, the further the electron is from the nucleus, and hence, the greater the energy in the atom. Each principal energy level is divided into sublevels corresponding to the number *n* of the principal energy level: thus, principal energy level 4 has four sublevels, principal energy level 5 has five, and so on.

**orbital patterns.** The four basic types of orbital patterns are designated as *s, p, d,* and *f.* The *s* shape might be described as spherical, which means that in an *s* orbital, the total electron cloud will probably end up being more or less like a sphere.

The *p* shape is like a figure eight around the nucleus; the *d* like two figure eights meeting at the nucleus; and the *f* orbital pattern is so complex that most basic chemistry textbooks do not even attempt to explain it. In any case, these orbital patterns do not indicate the exact path of an electron. Think of it, instead, in this way: if you could take millions of photographs of the electron during a period of a few seconds, the resulting blur of images in a *p* orbital, for instance, would somewhat describe the shape of a figure eight.

Since the highest energy levels of the transition metals begin at principal energy level 4, we will dispense with a discussion of the first three energy levels. The reader is encouraged to consult the Electrons essay, as well as the essay on Families of Elements, for a more detailed discussion of the ways in which these energy levels are filled for elements on periods 1 through 3.

## Orbital Filling and the Periodic Table

If all elements behaved as they "should," the pattern of orbital filling would be as follows. In a given principal energy level, first the two slots available to electrons on the *s* sublevel are filled, then the six slots on the *p* sublevel, then the 10 slots on the *d* sublevel. The *f* sublevel, which is fourth to be filled, comes into play only at principal energy level 4, and it would be filled before elements began adding valence electrons to the *s* sublevel on the next principal energy level.

That might be the way things "should" happen, but it is not the way that they do happen. The list that follows shows the pattern by which

orbitals are filled from sublevel 3*p* onward. Following each sublevel, in parentheses, is the number of "slots" available for electrons in that shell. Note that in several places, the pattern of filling defies the ideal order described in the preceding paragraph.

**Orbital Filling by Principal Energy Level and Sublevel from 3*p* Onward:**

- 3*p* (6)
- 4*s* (2)
- 3*d* (10)
- 4*p* (6)
- 5*s* (2)
- 4*d* (10)
- 5*p* (6)
- 6*s* (2)
- 4*f* (14)
- 5*d* (10)
- 6*p* (6)
- 7*s* (2)
- 5*f* (14)
- 6*d* (10)

The 44 representative elements follow a regular pattern of orbital filling through the first 18 elements. By atomic number 18, argon, 3*p* has been filled, and at that point element 19 (potassium) would be expected to begin filling row 3*d.* However, instead it begins filling 4*s,* to which calcium (20) adds the second and last valence electron. It is here that we come to the transition metals, distinguished by the fact that they fill the *d* orbitals.

Note that none of the representative elements up to this point, or indeed any that follow, fill the *d* orbital. (The *d* orbital could not come into play before Period 3 anyway, because at least three sublevels—corresponding to principal energy level 3—are required in order for there to be a *d* orbital.) In any case, when the representative elements fill the *p* orbitals of a given energy level, they skip the *d* orbital and go on to the next principal energy level, filling the *s* orbitals. Filling of the *d* orbital on the preceding energy level only occurs with the transition metals: in other words, on period 4, transition metals fill the 3*d* sublevel, and so on as the period numbers increase.

## Distinguishing the Transition Metals

Given the fact that it is actually the representative elements that skip the *d* sublevels, and the transition metals that go back and fill them, one might wonder if the names "representative" and "transition" (implying an interruption) should be reversed. But it is the transition metals that are the exception to the rule, for two reasons. First of all, as we have seen, they are the only elements that fill the *d* orbitals.

Secondly, they are the only elements whose outer-shell electrons are on two different principal energy levels. The orbital filling patterns of transition metals can be identified thus: n*s*(n-1)*d*, where *n* is the number of the period on which the element is located. For instance, zinc, on period 4, has an outer shell of $4s^2 3d^{10}$. In other words, it has two electrons on principal energy level 4, sublevel 4*s*—as it "should." But it also has 10 electrons on principal energy level 3, sublevel 3*d*. In effect, then, the transition metals "go back" and fill in the *d* orbitals of the preceding period.

There are further complications in the patterns of orbital filling for the transition metals, which will only be discussed in passing here as a further explanation as to why these elements are not "representative." Most of them have two *s* valence electrons, but many have one, and palladium has zero. Nor do they add their *d* electrons in regular patterns. Moving across period 4, for instance, the number of electrons in the *d* orbital "should" increase in increments of 1, from 1 to 10. Instead the pattern goes like this: 1, 2, 3, 5, 5, 6, 7, 8, 10, 10.

**LANTHANIDES AND ACTINIDES.** The lanthanides and actinides are set apart even further from the transition metals. In most versions of the periodic table, lanthanum (57) is followed by hafnium (72) in the transition metals section of the chart. Similarly, actinium (89) is followed by rutherfordium (104). The "missing" metals—lanthanides and actinides respectively—are listed at the bottom of the chart. There are reasons for this, as well as for the names of these groups.

After the 6*s* orbital fills with the representative element barium (56), lanthanum does what a transition metal does—it begins filling the 5*d* orbital. But after lanthanum, something strange happens: cerium (58) quits filling 5*d,* and moves to fill the 4*f* orbital. The filling of that orbital continues throughout the entire lanthanide series, all the way to lutetium (71). Thus lanthanides can be defined as those metals that fill the 4*f* orbital; however, because lanthanum

exhibits similar properties, it is usually included with the lanthanides.

A similar pattern occurs for the actinides. The 7*s* orbital fills with radium (88), after which actinium (89) begins filling the 6*d* orbital. Next comes thorium, first of the actinides, which begins the filling of the 5*f* orbital. This is completed with element 103, lawrencium. Actinides can thus be defined as those metals that fill the 5*f* orbital; but again, because actinium exhibits similar properties, it is usually included with the actinides.

## REAL-LIFE APPLICATIONS

### Survey of the Transition Metals

The fact that the transition elements are all metals means that they are lustrous or shiny in appearance, and malleable, meaning that they can be molded into different shapes without breaking. They are excellent conductors of heat and electricity, and tend to form positive ions by losing electrons.

Generally speaking, metals are hard, though a few of the transition metals—as well as members of other metal families—are so soft they can be cut with a knife. Like almost all metals, they tend to have fairly high melting points, and extremely high boiling points.

Many of the transition metals, particularly those on periods 4, 5, and 6, form useful alloys—mixtures containing more than one metal—with one another, and with other elements. Because of their differences in electron configuration, however, they do not always combine in the same ways, even within an element. Iron, for instance, sometimes releases two electrons in chemical bonding, and at other times three.

**ABUNDANCE OF THE TRANSITION METALS.** Iron is the fourth most abundant element on Earth, accounting for 4.71% of the elemental mass in the planet's crust. Titanium ranks 10th, with 0.58%, and manganese 13th, with 0.09%. Several other transition metals are comparatively abundant: even gold is much more abundant than many other elements on the periodic table. However, given the fact that only 18 elements account for 99.51% of Earth's crust, the percentages for elements outside of the top 18 tend to very small.

In the human body, iron is the 12th most abundant element, constituting 0.004% of the body's mass. Zinc follows it, at 13th place, accounting for 0.003%. Again, these percentages may not seem particularly high, but in view of the fact that three elements—oxygen, carbon, and hydrogen—account for 93% of human elemental body mass, there is not much room for the other 10 most common elements in the body. Transition metals such as copper are present in trace quantities within the body as well.

**DIVIDING THE TRANSITION METALS INTO GROUPS.** There is no easy way to group the transition metals, though certain of these elements are traditionally categorized together. These do not constitute "families" as such, but they do provide useful ways to break down the otherwise rather daunting 40-element lineup of the transition metals.

In two cases, there is at least a relation between group number on the periodic table and the categories loosely assigned to a collection of transition metals. Thus the "coinage metals"—copper, silver, and gold—all occupy Group 9 on the periodic table. These have traditionally been associated with one another because their resistance to oxidation, combined with their malleability and beauty, has made them useful materials for fashioning coins.

Likewise the members of the "zinc group"—zinc, cadmium, and mercury—occupy Group 10 on the periodic table. These, too, have often been associated as a miniature unit due to common properties. Members of the "platinum group"—platinum, iridium, osmium, palladium, rhodium, and ruthenium—occupy a rectangle on the table, corresponding to periods 5 and 6, and groups 6 through 8. What actually makes them a "group," however, is the fact that they tend to appear together in nature.

Iron, nickel, and cobalt, found alongside one another on Period 4, may be grouped together because they are all magnetic to some degree or another. This is far from the only notable characteristic about such metals, but provides a convenient means of further dividing the transition metals into smaller sections.

To the left of iron on the periodic table is a rectangle corresponding to periods 4 through 6, groups 4 through 7. These 11 elements—titani-

um, zirconium, hafnium, vanadium, niobium, tantalum, chromium, molybdenum, tungsten, manganese, and rhenium—are referred to here as "alloy metals." This is not a traditional designation, but it is nonetheless useful for describing these metals, most of which form important alloys with iron and other elements.

One element was left out of the "rectangle" described in the preceding paragraph. This is technetium, which apparently does not occur in nature. It is lumped in with a final category, "rare and artificial elements."

It should be stressed that there is nothing hard and fast about these categories. The "alloy metals" are not the only ones that form alloys; nickel is used in coins, though it is not called a coinage metal; and platinum could be listed with gold and silver as "precious metals." Nonetheless, the categories used here seem to provide the most workable means of approaching the many transition metals.

## COINAGE METALS

**GOLD.** Gold almost needs no introduction: virtually everyone knows of its value, and history is full of stories about people who killed or died for this precious metal. Part of its value springs from its rarity in comparison to, say iron: gold is present on Earth's crust at a level of about 5 parts per billion (ppb). Yet as noted earlier, it is more abundant than some metals. Furthermore, due to the fact that it is highly unreactive (reactivity refers to the tendency for bonds between atoms or molecules to be made or broken in such a way that materials are transformed), it tends to be easily separated from other elements.

This helps to explain the fact that gold may well have been the first element ever discovered. No ancient metallurgist needed a laboratory in which to separate gold; indeed, because it so often keeps to itself, it is called a "noble" metal—meaning, in this context, "set apart." Another characteristic of gold that made it valuable was its great malleability. In fact, gold is the most malleable 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 $ft^2$ (6.3 $m^2$).

Gold is one of the few metals that is not silver, gray, or white, and its beautifully distinctive color caught the eyes of metalsmiths and royalty from the beginning of civilization. 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. The Romans called it *aurum* ("shining dawn"), which explains its chemical symbol, Au.

Early chemistry had its roots among the medieval alchemists, who sought in vain to turn plain metals into gold. Likewise the history of European conquest in the New World is filled with bitter tales of conquistadors, lured by gold, who wiped out entire nations of native peoples.

At one time, gold was used in coins, and nations gauged the value of their currency in terms of the gold reserves they possessed. Few coins today—with special exceptions, such as the South African Krugerrand—are gold. Likewise the United States, for instance, went off the gold standard (that is, ceased to tie its currency to gold reserves) in the 1930s; nonetheless, the federal government maintains a vast supply of gold bullion at Fort Knox in Kentucky.

Gold is as popular as ever for jewelry and other decorative objects, of course, but for the most part, it is too soft to have many other commercial purposes. One of the few applications for gold, a good conductor of electricity, is in some electronic components. Also, the radioactive gold-198 isotope is sometimes implanted in tissues as a means of treating forms of cancer.

**SILVER.** Like gold, silver has been a part of human life from earliest history. Usually it is considered less valuable, though some societies have actually placed a higher value on silver because it is harder and more durable than gold. In the seventh century B.C., the Lydian civilization of Asia Minor (now Turkey) created the first coins using silver, and in the sixth century B.C., the Chinese began making silver coins. Succeeding dynasties in China continued to mint these coins, round with square holes in them, until the early twentieth century.

The Romans called silver *argentum,* and therefore today its chemical symbol is Ag. Its uses are much more varied than those of gold, both because of its durability and the fact that it is less expensive. Alloyed with copper, which adds strength to it, it makes sterling silver, used in coins, silverware, and jewelry. Silver nitrate compounds are used in silver plating, applied in mir-

rors and tableware. (Most mirrors today, however, use aluminum.)

Like gold, silver was once widely used for coinage, and silver coins are still more common than their gold counterparts. In 1963, however, the United States withdrew its silver certifications, paper currency exchangeable for silver. Today, silver coins are generally issued in special situations, such as to commemorate an event.

A large portion of the world's silver supply is used by photographers for developing pictures. In addition, because it is an excellent conductor of heat and electricity, silver has applications in the electronics industry; however, its expense has led many manufacturers to use copper or aluminum instead. Silver is also present, along with zinc and cadmium, in cadmium batteries. Like gold, though to a much lesser extent, it is still an important jewelry-making component.

**COPPER.** Most people think of pennies as containing copper, but 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 $0.01, a penny is actually made of zinc with a thin copper coating. Yet copper has long been a commonly used coinage metal, and long before that, humans used it for other purposes.

Seven thousand years ago, the peoples of the Tigris-Euphrates river valleys, in what is now Iraq, were mining and using copper, and later civilizations combined copper with zinc to make bronze. Indeed, the history of prehistoric and ancient humans' technological development is often divided according to the tools they made, the latter two of which came from transition metals: the Stone Age, the Bronze Age (c. 3300-1200 B.C.), and the Iron Age.

Thus, by the time the Romans dubbed copper *cuprum* (from whence its chemical symbol, Cu, comes), copper in various forms had long been in use. Today copper is purified by a form of electrolysis, in which impurities such as iron, nickel, arsenic, and zinc are removed. Other "impurities" often present in copper ore include gold, silver, and platinum, and the separation of these from the copper pays for the large amounts of electricity used in the electrolytic process.

Like the other coinage metals, copper is an extremely efficient conductor of heat and electricity, and because it is much less expensive than the other two, pure copper is widely used for electrical wiring. Because of its ability to conduct heat, copper is also applied in materials used for making heaters, as well as for 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.

Copper is also like its two close relatives in that it resists corrosion, and this makes it ideal for plumbing. Its use in making coins resulted from its anti-corrosive qualities, combined with its beauty: like gold, copper has a distinctive color. This aesthetic quality led to the use of copper in decorative applications as well: many old buildings used copper roofs, and the Statue of Liberty is covered in 300 thick copper plates.

Why, then, is the famous statue not copper-colored? Because copper does eventually corrode when exposed to air for long periods of time. Over time, it develops a thin layer of black copper oxide, and as the years pass, carbon dioxide in the air leads to the formation of copper carbonate, which imparts a greenish color.

The human body is about 0.0004% copper, though as noted, larger quantities of copper can be toxic. Copper is found in foods such as shellfish, nuts, raisins, and dried beans. Whereas human blood has hemoglobin, a molecule with an iron atom at the center, the blood of lobsters and other large crustaceans contains hemocyanin, in which copper performs a similar function.

## The Zinc Group

**ZINC.** Together with copper, zinc appeared in another alloy that, like bronze, helped define the ancient world: brass. (The latter is mentioned in the Bible, for instance in the Book of Daniel, when King Nebuchadnezzar dreams of a statue containing brass and other substances, symbolizing various empires.) Used at least from the first millennium B.C. onward, brass appeared in coins and ornaments throughout Asia Minor. Though it is said that the Chinese purified zinc in about A.D. 1000, the Swiss alchemist Paracelsus (1493-1541) is usually credited with first describing zinc as a metal.

Bluish-white, with a lustrous sheen, zinc is found primarily in the ore sulfide sphalerite. The largest natural deposits of zinc are in Australia and the United States, and after mining, the metal is subjected to a purification and reduction

process involving carbon. Zinc is used in galvanized steel, developed in the eighteenth century by Italian physicist Luigi Galvani (1737-1798).

Just as a penny is not really copper but zinc, "tin" roofs are usually made of galvanized steel. Highly resistant to corrosion, galvanized steel finds application in everything from industrial equipment to garbage cans. Zinc oxide is applied in textiles, batteries, paints, and rubber products, while luminous zinc sulfide appears in television screens, movie screens, clock dials, and fluorescent light bulbs.

Zinc phosphide is used as a rodent poison. Like several other transition metals, zinc is a part of many living things, yet it can be toxic in large quantities or specific compounds. For a human being, inhaling zinc oxide causes involuntary shaking. On the other hand, humans and many animals require zinc in their diets for the digestion of proteins. Furthermore, it is believed that zinc contributes to the healing of wounds and to the storage of insulin in the pancreas.

**CADMIUM.** In 1817, German chemist Friedrich Strohmeyer (1776-1835) was working as an inspector of pharmacies for the German state of Hanover. While making his rounds, he discovered that one pharmacy had a sample of zinc carbonate labeled as zinc oxide, and while inspecting the chemical in his laboratory, he discovered something unusual. If indeed it were zinc carbonate, it should turn into zinc oxide when heated, and since both compounds were white, there should be no difference in color. Instead, the mysterious compound turned a yellowish-orange.

Strohmeyer continued to analyze the sample, and eventually realized that he had discovered a new element, which he named after the old Greek term for zinc carbonate, *kadmeia.* Indeed, cadmium typically appears in nature along with zinc or zinc compounds. Silvery white and lustrous or shiny, cadmium is soft enough to be cut with a knife, but chemically it behaves much like zinc: hence the idea of a "zinc group."

Today cadmium is used in batteries, and for electroplating of other metals to protect them against corrosion. Because the cost of cadmium is high due to the difficulty of separating it from zinc, cadmium electroplating is applied only in specialized situations. Cadmium also appears in the control rods of nuclear power plants, where its ready absorption of neutrons aids in controlling the rate at which nuclear fission occurs.

Cadmium is highly toxic, and is believed to be the cause behind the outbreak of itai-itai ("ouch-ouch") disease in Japan in 1955. People ingested rice oil contaminated with cadmium, and experienced a number of painful side effects associated with cadmium poisoning: nausea, vomiting, choking, diarrhea, abdominal pain, headaches, and difficulty breathing.

**MERCURY.** One of only two elements—along with bromine—that appears in liquid form at room temperature, mercury is both toxic and highly useful. The Romans called it *hydragyrum* ("liquid silver"), from whence comes its chemical symbol, Hg. Today, however, it is known by the name of the Romans' god Mercury, the nimble and speedy messenger of the gods. Mercury comes primarily from a red ore called cinnabar, and since it often appears in shiny globules that form outcroppings from the cinnabar, it was relatively easy to discover.

Several things are distinctive about mercury, including its bright silvery color. But nothing distinguishes it as much as its physical properties—not only its liquidity, but the fact that it rolls rapidly, like the fleet-footed god after which it is named. Its surface tension (the quality that causes it to bead) is six times greater than that of water, and for this reason, mercury never wets the surfaces with which it comes in contact.

Mercury, of course, is widely used in thermometers, an application for which it is extremely well-suited. In particular, it expands at a uniform rate when heated, and thus a mercury thermometer (unlike earlier instruments, which used water, wine, or alcohol) can be easily calibrated. (Note that due to the toxicity of the element, mercury thermometers in schools are being replaced by other types of thermometers.) At temperatures close to absolute zero, mercury loses its resistance to the flow of electric current, and therefore it presents a promising area of research with regard to superconductivity.

Even with elements present in the human body, such as zinc, there is a danger of toxicity with exposure to large quantities. Mercury, on the other hand, does not occur naturally in the human body, and is therefore extremely dangerous. Because it is difficult for the body to eliminate, even small quantities can accumulate and exert their poisonous effects, resulting in disor-

ders of the nervous system. In fact, the phrase "mad as a hatter" refers to the symptoms of mercury poisoning suffered by hatmakers of the nineteenth century, who used a mercury compound in making hats of beaver and fur.

## Magnetic Metals

**IRON.** In its purest form, iron is relatively soft and slightly magnetic, but when hardened, it becomes much more so. As with several of the elements discovered long ago, iron has a chemical symbol (Fe) reflecting an ancient name, the Latin *ferrum.* But long before the Romans' ancestors arrived in Italy, the Hittites of Asia Minor were purifying iron ore by heating it with charcoal over a hot flame.

The Hittites jealously guarded their secret, which gave them a technological advantage over enemies such as the Egyptians. But when Hittite civilization crumbled in the wake of an invasion by the mysterious "Sea Peoples" in about 1200 B.C., knowledge of ore smelting spread throughout the ancient world. Thus began the Iron Age, in which ancient technology matured greatly. (It should be noted that the Bantu peoples, in what is now Nigeria and neighboring countries, developed their own ironmaking techniques a few centuries later, apparently without benefit of contact with any civilization exposed to Hittite techniques.)

Ever since ancient times, iron has been a vital part of human existence, and with the growth of industrialization during the eighteenth century, demand for iron only increased. But heating iron ore with charcoal required the cutting of trees, and by the latter part of that century, England's forests had been so badly denuded that British ironmakers sought a new means of smelting the ore. It was then that British inventor Abraham Darby (1678?-1717) developed a method for making coke from soft coal, which was abundant throughout England. Adoption of Darby's technique sped up the rate of industrialization in England, and thus advanced the entire Industrial Revolution soon to sweep the Western world.

Symbolic of industrialism was iron in its many forms: pig iron, ore smelted in a coke-burning blast furnace; cast iron, a variety of mixtures containing carbon and/or silicon; wrought iron, which contains small amounts of various other elements, such as nickel, cobalt, copper, chromium, and molybdenum; and most of all steel. Steel is a mixture of iron with manganese and chromium, purified with a blast of hot air in the Bessemer converter, named after English inventor Henry Bessemer (1813-1898). Modern techniques of steelmaking improved on Bessemer's design by using pure oxygen rather than merely hot air.

The ways in which iron is used are almost too obvious (and too numerous) to mention. If iron and steel suddenly ceased to exist, there could be no skyscrapers, no wide-span bridges, no ocean liners or trains or heavy machinery or automobile frames. Furthermore, alloys of steel with other transition metals, such as tungsten and niobium, possess exceptionally great strength, and find application in everything from hand tools to nuclear reactors. Then, of course, there are magnets and electromagnets, which can only be made of iron and/or one of the other magnetic elements, cobalt and nickel.

In the human body, iron is a key part of hemoglobin, the molecule in blood that transports oxygen from the lungs to the cells. If a person fails to get sufficient quantities of iron—present in foods such as red meat and spinach—the result is anemia, characterized by a loss of skin color, weakness, fainting, and heart palpitations. Plants, too, need iron, and without the appropriate amounts are likely to lose their color, weaken, and die.

**COBALT.** Isolated in about 1735 by Swedish chemist Georg Brandt (1694-1768), cobalt was the first metal discovered since prehistoric, or at least ancient, times. The name comes from *Kobald,* German for "underground gnome," and this reflects much about the early history of cobalt. In legend, the Kobalden were mischievous sprites who caused trouble for miners, and in real life, ores containing the element that came to be known as cobalt likewise caused trouble to men working in mines. Not only did these ores contain arsenic, which made miners ill, but because cobalt had no apparent value, it only interfered with their work of extracting other minerals.

Yet cobalt had been in use by artisans long before Brandt's isolated the element. The color of certain cobalt compounds is a brilliant, shocking blue, and this made it popular for the coloring of pottery, glass, and tile. The element, which makes up less than 0.002% of Earth's crust, is found today primarily in ores extracted from mines in

Canada, Zaire, and Morocco. One of the most important uses of cobalt is in a highly magnetic alloy known as alnico, which also contains iron, nickel, and aluminum. Combined with tungsten and chromium, cobalt makes stellite, a very hard alloy used in drill bits. Cobalt is also applied in jet engines and turbines.

**NICKEL.** Moderately magnetic in its pure form, nickel had an early history much like that of cobalt. English workers mining copper were often dismayed to find a metal that looked like copper, but was not, and they called it "Old Nick's copper"—meaning that it was a trick played on them by Old Nick, or the devil. The Germans gave it a similar name: *Kupfernickel,* or "imp copper."

Though nickel was not identified as a separate metal by Swedish mineralogist Axel Fredrik Cronstedt (1722-1765) until the eighteenth century, alloys of copper, silver, and nickel had been used as coins even in ancient Egypt. Today, nickel is applied, not surprisingly, in the American five-cent piece—that is, the "nickel"—made from an alloy of nickel and copper. Its anti-corrosive nature also provides a number of other applications for nickel: alloyed with steel, for instance, it makes a protective layer for other metals.

## The Platinum Group

**PLATINUM.** First identified by an Italian physician visiting the New World in the mid-sixteenth century, platinum—now recognized as a precious metal—was once considered a nuisance in the same way that nickel and cadmium were. Miners, annoyed with the fact that it got in the way when they were looking for gold, called it *platina,* or "little silver." One of the reasons why platinum did not immediately catch the world's fancy is because it is difficult to extract, and typically appears with the other metals of the "platinum group": iridium, osmium, palladium, rhodium, and ruthenium.

Only in 1803 did English physician and chemist William Hyde Wollaston (1766-1828) develop a means of extracting platinum, and when he did, he discovered that the metal could be hammered into all kinds of shapes. Platinum proved such a success that it made Wollaston financially independent, and he retired from his medical practice at age 34 to pursue scientific research. Today, platinum is used in everything from thermometers to parts for rocket engines, both of which take advantage of its ability to withstand high temperatures.

**IRIDIUM AND OSMIUM.** In the same year that Wollaston isolated platinum, three French chemists applied a method of extracting it with a mixture of nitric and hydrochloric acids. The process left a black powder that they were convinced was a new element, and in 1804 English chemist Smithson Tennant (1761-1815) gave it the name iridium. Iris was the Greek goddess of the rainbow, and the name reflected the element's brilliant, multi-colored sheen. As with platinum, iridium is used today in a number of ways, particularly for equipment such as laser crystals that must withstand high temperatures. (In addition, one particular platinum-iridium bar provides the standard measure of a kilogram.)

Tennant discovered a second element in 1804, also from the residue left over from the acid process for extracting platinum. This one had a distinctive smell when heated, so he named it osmium after *osme,* Greek for "odor." In 1898, Austrian chemist Karl Auer, Baron von Welsbach (1858-1929), developed a light bulb using osmium as a filament, the material that is heated. Though osmium proved too expensive for commercial use, Auer's creation paved the way for the use of another transition metal, tungsten, in making long-lasting filaments. Osmium, which is very hard and resistant to wear, is also used in electrical devices, fountain-pen tips, and phonograph needles.

**PALLADIUM, RHODIUM, AND RUTHENIUM.** By the time Tennant isolated osmium, Wollaston had found yet another element that emerged from the refining of platinum with nitric and hydrochloric acids. This was palladium, named after a recently discovered asteroid, Pallas. Soft and malleable, palladium resists tarnishing, which makes it valuable to the jewelry industry. Combined with yellow gold, it makes the alloy known as white gold. Because palladium has the unusual ability of absorbing up to 900 times its volume in hydrogen, it provides a useful means of extracting that element.

Also in 1805, Wollaston discovered rhodium, which he named because it had a slightly red color. The density of rhodium is lower, and the melting point higher, than for most of the platinum group elements, and it is often used as an alloy to harden platinum. As with many elements

in this group, it has a number of high-temperature applications. When electroplated, it is highly reflective, and this makes it useful as a material for optical instruments.

The element that came to be known as ruthenium had been detected several times before 1844, when Russian chemist Carl Ernest Claus (1796-1864) finally identified it as a distinct element. Thus it was the only platinum group element in whose isolation neither Tennant nor Wollaston played a leading role. Since it had been found in Russia, the element was called ruthenium, in honor of that country's ancient name, Ruthenia.

## Alloy Metals

The elements described here as "alloy metals" will be treated briefly, but the amount of space given to them here does not reflect their importance to civilization. Several of these are relatively abundant, and many—titanium, tungsten, manganese, chromium and others—are vital parts of daily life. However, due to space considerations, the treatment of these metals that follows is a regrettably abbreviated one.

As suggested by the informal name given to them here, they are often applied in alloys, typically with other transition metals such as iron, or with other "alloy metals." They are also used in a variety of compounds for a wide variety of applications.

## Titanium, Zirconium, and Hafnium

English clergyman and amateur scientist William Gregor (1761-1817) in 1791 noticed what he called "a new metallic substance" in a mineral called menchanite, which he found in the Menachan region of Cornwall, England. Four years later, German chemist Martin Heinrich Klaproth (1743-1817) studied menchanite and found that it contained a new element, which he named titanium after the Titans of Greek mythology. Only in 1910, however, was the element isolated. Due to its high strength-to-weight ratio, titanium is applied today in alloys used for making airplanes and spacecraft. It is also used in white paints and in a variety of other combinations, mostly in alloys containing other transition metals, as well as in compounds with nonmetals such as oxygen.

Six years before he identified titanium, in 1789, Klaproth had found another element, which he named zirconium after the mineral zircon in which it was found. Zircon had been in use for many centuries, and another zirconium-containing mineral, jacinth, is mentioned in the Bible. As with titanium, there was a long period from identification to isolation, which did not occur until 1914. Zirconium alloys are used today in a number of applications, including superconducting magnets and as a construction metal in nuclear power plants. Compounds including zirconium also have a variety of uses, ranging from furnace linings to poison ivy lotion.

Because it is almost always found with zirconium, hafnium—named after the ancient name of Copenhagen, Denmark—proved extremely difficult to isolate. Only in 1923 was it isolated, using x-ray analysis, and today it is applied primarily in light bulb filaments and electrodes. Sometimes it is accidentally "applied," when zirconium is actually the desired metal, because the two are so difficult to separate.

**Vanadium, tantalum, and niobium.** Vanadium, named after the Norse goddess Vanadis or Freyja, was first identified in 1801, but only isolated in 1867. It is often applied in alloys with steel, and sometimes used for bonding steel and titanium.

Tantalum and niobium are likewise named after figures from mythology—in this case, Greek. These two elements appear together so often that their identification as separate substances was a long process, involving numerous scientists and heated debates. For this reason, alloys involving tantalum—valued for its high melting point—usually include niobium as well.

**Chromium, tungsten, and manganese, and other metals.** Because it displays a wide variety of colors, chromium was named after the Greek word for "color." It is used in chrome and tinted glass, and as a strengthening agent for stainless steel. Tungsten likewise strengthens steel, in large part because it has the highest melting point of any metal: 6,170°F (3,410°C). Its name comes from a Swedish word meaning "heavy stone," and its chemical symbol (W) refers to the ore named wolframite, in which it was first discovered. Its high resistance to heat gives tungsten alloys applications in areas ranging from light bulb filaments to furnaces to missiles.

## KEY TERMS

**ACTINIDES:** Those transition metals that fill the 5*f* orbital. Because actinium—which does not fill the 5*f* orbital—exhibits characteristics similar to those of the actinides, it is usually considered part of the actinides family.

**ALLOY:** A mixture containing more than one metal.

**ELECTROLYSIS:** The use of an electric current to cause a chemical reaction.

**ELECTRON CLOUD:** A term used to describe the pattern formed by orbitals.

**GROUPS:** Columns on the periodic table of elements. These are ordered according to the numbers of valence electrons in the outer shells of the atoms for the elements represented.

**INNER TRANSITION METALS:** The lanthanides and actinides, both of which fill the *f* orbitals. For this reason, they are usually treated separately.

**ION:** An atom or group of atoms 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. Isotopes may be either stable or unstable. The latter type, known as radioisotopes, are radioactive.

**IUPAC SYSTEM:** A version of the periodic table of elements, authorized by the International Union of Pure and Applied Chemistry (IUPAC), which numbers all groups on the table from 1-18. Thus in the IUPAC system, in use primarily outside of North America, both the representative or main-group elements and the transition metals are numbered.

**LANTHANIDES:** The transition metals that fill the 4*f* orbital. Because lanthanum—which does not fill the 4*f* orbital—exhibits characteristics similar to those of the lanthanides, it is usually considered part of the lanthanide family.

**NORTH AMERICAN SYSTEM:** A version of the periodic table of elements that only numbers groups of elements in which the number of valence electrons equals the group number. Hence the transition metals are usually not numbered in this system. Some North American charts, however, do provide group numbers for transition metals by including an "A" after the group numbers for representative or main-group elements, and "B" after those of transition metals.

**ORBITAL:** A pattern of probabilities indicating the regions that may be occupied by an electron. The higher the principal energy level, the more complex the pattern of orbitals.

**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 (in atomic mass units) for that particular element. Elements are arranged in groups or columns, as well as in rows or periods, according to specific aspects of their valence electron configurations.

**PERIODS:** Rows on the periodic table of elements. These represent successive principal energy levels for the valence electrons in the atoms of the elements involved. Elements in the transition metal family occupy periods 4, 5, 6, or 7.

## KEY TERMS CONTINUED

**PRINCIPAL ENERGY LEVEL:** A value indicating the distance that an electron may move away from the nucleus of an atom. This is designated by a whole-number integer, beginning with 1 and moving upward. The higher the principal energy level, the greater the energy in the atom, and the more complex the pattern of orbitals. Elements in the transition metal family have principal energy levels of 4, 5, 6, or 7.

**RADIOACTIVITY:** A term describing a phenomenon whereby certain isotopes known as radioisotopes are subject to a form of decay brought about by the emission of high-energy particles. "Decay" does not mean that the isotope "rots"; rather, it decays to form another isotope until eventually (though this may take a long time), it becomes stable.

**REACTIVITY:** The tendency for bonds between atoms or molecules to be made or broken in such a way that materials are transformed.

**REPRESENTATIVE OR MAIN-GROUP ELEMENTS:** The 44 elements in Groups 1 through 8 on the periodic table of elements in the North American system, for which the number of valence electrons equals the group number. (The only exception is helium.) In the IUPAC system, these elements are assigned group numbers 1, 2, and 13 through 18. (In these last six columns on the IUPAC chart, there is no relation between the number of valence electrons and group number.)

**SHELL:** The orbital pattern of the valence electrons at the outside of an atom.

**SUBLEVEL:** A region within the principal energy level occupied by electrons in an atom. Whatever the number *n* of the principal energy level, there are *n* sublevels. At each principal energy level, the first sublevel to be filled is the one corresponding to the *s* orbital pattern, followed by the *p* and then the *d* pattern.

**TRANSITION METALS:** A group of 40 elements, which are not assigned a group number in the version of the periodic table of elements known as the North American system. These are the only elements that fill the *d*orbital. In addition, the transition metals—unlike the representative or main-group elements—have their valence electrons on two different principal energy levels. Though the lanthanides and actinides are considered inner transition metals, they are usually treated separately.

**VALENCE ELECTRONS:** Electrons that occupy the highest principal energy level in an atom. These are the electrons involved in chemical bonding.

Likewise manganese, first identified in the mid-eighteenth century, is extraordinarily strong. Its major use is in steelmaking. In addition, compounds such as manganese oxide are used in fertilizers. Other alloy metals include rhenium (identified only in 1925) and molybdenum. These two are often applied in alloys together, and with tungsten, for a variety of industrial purposes.

### Rare and Artificial Elements

**RARE EARTH-LIKE ELEMENTS.** Though they are not part of the lanthanide series, scandium and yttrium share many properties with those elements, once known as the "rare earths." (In this context, "rarity" refers not so much to scarcity as to difficulty of extraction.) Furthermore, like most of the lan-

thanides, these two elements were first discovered in Scandinavia.

Their origin is reflected in the name given by Swedish chemist Lars Nilson (1840-1899) to scandium, which he discovered in 1876. As for yttrium, it came from the complex mineral known as ytterite, from whence emerged many of the lanthanides. Yttrium is used in alloys to impart strength, and has a wide if specialized array of applications. Scandium has no important uses.

**ARTIFICIAL ELEMENTS.** Technetium, with an atomic number of 43, is unusual in that it is one of the few elements with an atomic number less than 92 that does not occur in nature. This is reflected in its name, from the Greek *technetos,* meaning "artificial." The strange thing is that technetium, produced in a laboratory in 1936, does occur naturally in the universe—but it seems to be found only in the spectral lines from older stars, and not in those of younger stars such as our Sun.

The other elements in the transition metals family are referred to as "transuranium elements," meaning that they have atomic numbers higher than that of uranium (92). These have all been created artificially; all are highly radioactive; few survive for more than a few minutes (at most); and few have applications in ordinary life.

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# ACTINIDES

## CONCEPT

The actinides (sometimes called actinoids) occupy the "bottom line" of the periodic table—a row of elements normally separated from the others, placed at the foot of the chart along with the lanthanides. Both of these families exhibit unusual atomic characteristics, properties that set them apart from the normal sequence on the periodic table. But there is more that distinguishes the actinides, a group of 14 elements along with the transition metal actinium. Only four of them occur in nature, while the other 10 have been produced in laboratories. These 10 are classified, along with the nine elements to the right of actinium on Period 7 of the periodic table, as transuranium (beyond uranium) elements. Few of these elements have important applications in daily life; on the other hand, some of the lower-number transuranium elements do have specialized uses. Likewise several of the naturally occurring actinides are used in areas ranging from medical imaging to powering spacecraft. Then there is uranium, "star" of the actinide series: for centuries it seemed virtually useless; then, in a matter of years, it became the most talked-about element on Earth.

## HOW IT WORKS

### The Transition Metals

Why are actinides and lanthanides set apart from the periodic table? This can best be explained by reference to the transition metals and their characteristics. Actinides and lanthanides are referred to as inner transition metals, because, although they belong to this larger family, they are usually considered separately—rather like grown children who have married and started families of their own.

The qualities that distinguish the transition metals from the representative or main-group elements on the periodic table are explained in depth within the Transition Metals essay. The reader is encouraged to consult that essay, as well as the one on Families of Elements, which further places the transition metals within the larger context of the periodic table. Here these specifics will be discussed only briefly.

**ORBITAL PATTERNS OF THE TRANSITION METALS.** The transition metals are distinguished by their configuration of valence electrons, or the outer-shell electrons involved in chemical bonding. Together with the core electrons, which are at lower energy levels, valence electrons move in areas of probability referred to as orbitals. The pattern of orbitals is determined by the principal energy level of the atom, which indicates a distance that an electron may move away from the nucleus.

Each principal energy level is divided into sublevels corresponding to the number *n* of the principal energy level. The actinides, which would be on Period 7 if they were included on the periodic table with the other transition metals, have seven principal energy levels. (Note that period number and principal energy level number are the same.) In the seventh principal energy level, there are seven possible sublevels.

The higher the energy level, the larger the number of possible orbital patterns, and the more complex the patterns. Orbital patterns loosely define the overall shape of the electron cloud, but this does not necessarily define the paths along which the electrons move. Rather, it

means that if you could take millions of photographs of the electron during a period of a few seconds, the resulting blur of images would describe more or less the shape of a specified orbital.

The four basic types of orbital patterns are discussed in the Transition Metals essay, and will not be presented in any detail here. It is important only to know that, unlike the representative elements, transition metals fill the sublevel corresponding to the *d* orbitals. In addition, they are the only elements that have valence electrons on two different principal energy levels.

**LANTHANIDES AND ACTINIDES.** The lanthanides and actinides are further set apart even from the transition metals, due to the fact that these elements also fill the highly complex *f* orbitals. Thus these two families are listed by themselves. In most versions of the periodic table, lanthanum (57) is followed by hafnium (72) in the transition metals section of the chart; similarly, actinium (89) is followed by rutherfordium (104). The "missing" metals—lanthanides and actinides, respectively—are shown at the bottom of the chart.

The lanthanides can be defined as those metals that fill the 4*f* orbital. However, because lanthanum (which does not fill the 4*f* orbital) exhibits similar properties, it is usually included with the lanthanides. Likewise the actinides can be defined as those metals that fill the 5*f* orbital; but again, because actinium exhibits similar properties, it is usually included with the actinides.

## ISOTOPES

One of the distinguishing factors in the actinide family is its great number of radioactive isotopes. Two atoms may have the same number of protons, and thus be of the same element, yet differ in their number of neutrons—neutrally charged patterns alongside the protons at the nucleus. Such atoms are called isotopes, atoms of the same element having different masses.

Isotopes are represented symbolically in one of several ways. For instance, there is this format: ${}^{m}_{a}S$, where *S* is the chemical symbol of the element, *a* is the atomic number (the number of protons in its nucleus), and *m* the mass number—the sum of protons and neutrons. For the isotope known as uranium-238, for instance, this is shown as ${}^{238}_{92}U$.

Because the atomic number of any element is established, however, isotopes are usually represented simply with the mass number thus: ${}^{238}U$. They may also be designated with a subscript notation indicating the number of neutrons, so that this information can be obtained at a glance without it being necessary to do the arithmetic. For the uranium isotope shown here, this is written as ${}^{238}_{92}U_{146}$.

## RADIOACTIVITY

The term radioactivity describes a phenomenon whereby certain materials are subject to a form of decay brought about by the emission of high-energy particles, or radiation.

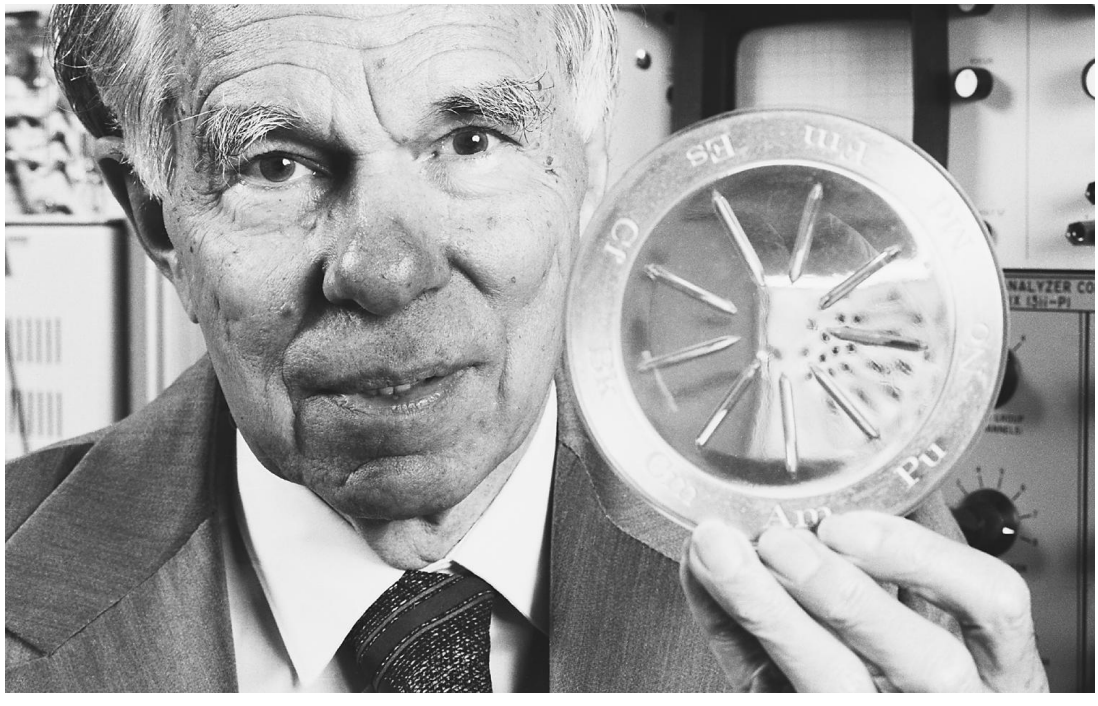
Types of particles emitted in radiation include:

- Alpha particles, or helium nuclei;
- Beta particles—either an electron or a subatomic particle called a positron;
- Gamma rays or other very high-energy electromagnetic waves.

Isotopes are either stable or unstable, with the unstable variety, known as radioisotopes, being subject to radioactive decay. In this context, "decay" does not mean "rot"; rather, a radioisotope decays by turning into another isotope. By continuing to emit particles, the isotope of one element may even turn into the isotope of another element.

Eventually the radioisotope becomes a stable isotope, one that is not subject to radioactive decay. This is a process that may take seconds, minutes, hours, days, years—and sometimes millions or even billions of years. The rate of decay is gauged by the half-life of a radioisotope sample: in other words, the amount of time it takes for half the nuclei (plural of nucleus) in the sample to become stable.

Actinides decay by a process that begins with what is known as K-capture, in which an electron of a radioactive atom is captured by the nucleus and taken into it. This is followed by the splitting, or fission, of the atom's nucleus. This fission produces enormous amounts of energy, as well as the release of two or more neutrons, which may in turn bring about further K-capture. This is called a chain reaction.




Glenn T. Seaborg holds a sample containing artificial elements between 94 and 102 on the periodic table. *(Roger Ressmeyer/Corbis. Reproduced by permission.)*

## REAL-LIFE APPLICATIONS

### The First Three Naturally Occurring Actinides

In the discussion of the actinides that follows, atomic number and chemical symbol will follow the first mention of an element. Atomic mass figures are available on any periodic table, and these will not be mentioned in most cases. The atomic mass figures for actinide elements are very high, as fits their high atomic number, but for most of these, figures are usually for the most stable isotope, which may exist for only a matter of seconds.

Though it gives its name to the group as a whole, actinium (Ac, 89) is not a particularly significant element. Discovered in 1902 by German chemist Friedrich Otto Giesel (1852-1927), it is found in uranium ores. Actinium is 150 times more radioactive than radium, a highly radioactive alkaline earth metal isolated around the same time by French-Polish physicist and chemist Marie Curie (1867-1934) and her husband Pierre (1859-1906).

**THORIUM.** More significant than actinium is thorium (Th, 90), first detected in 1815 by the renowned Swedish chemist Jons Berzelius (1779-1848). Berzelius promptly named the element after the Norse god Thor, but eventually concluded that what he had believed to be a new element was actually the compound yttrium phosphate. In 1829, however, he examined another mineral and indeed found the element he believed he had discovered 14 years earlier.

It 1898, Marie Curie and an English chemist named Gerhard Schmidt, working independently, announced that thorium was radioactive. Today it is believed that the enormous amounts of energy released by the radioactive decay of subterranean thorium and uranium plays a significant part in Earth's high internal temperature. The energy stored in the planet's thorium reserves may well be greater than all the energy available from conventional fossil and nuclear fuels combined.

Thorium appears on Earth in an abundance of 15 parts per million (ppm), many times greater than the abundance of uranium. With its high energy levels, thorium has enormous potential as a nuclear fuel. When struck by neutrons, thorium-232 converts to uranium-233, one of the few known fissionable isotopes—that is, isotopes that can be split to start nuclear reactions.

It is perhaps ironic that this element, with its potential for use in some of the most high-tech applications imaginable, is widely applied in a very low-tech fashion. In portable gas lanterns for camping and other situations without electric power, the mantle often contains oxides of thorium and cerium, which, when heated, emit a brilliant white light. Thorium is also used in the manufacture of high-quality glass, and as a catalyst in various industrial processes.

**PROTACTINIUM.** Russian chemist Dmitri Ivanovitch Mendeleev (1834-1907), father of the periodic table, used the table's arrangement of elements as a means of predicting the discovery of new substances: wherever he found a "hole" in the table, Mendeleev could say with assurance that a new element would eventually be found to fill it. In 1871, Mendeleev predicted the discovery of "eka-tantalum," an element that filled the space below the transition metal tantalum. (At this point in history, just two years after Mendeleev created the periodic table, the lanthanides and actinides had not been separated from the rest of the elements on the chart.)

Forty years after Mendeleev foretold its existence, two German chemists found what they thought might be Element 91. It had a half-life of only 1.175 minutes, and, for this reason, they named it "brevium." Then in 1918, Austrian physicist Lise Meitner (1878-1968)—who, along with Curie and French physicist Marguerite Perey (1909-1975) was one of several women involved in the discovery of radioactive elements—was working with German chemist Otto Hahn (1879-1968) when the two discovered another isotope of Element 91. This one had a much, much longer half-life: $3.25 \cdot 10^4$ years, or about five times as long as the entire span of human civilization.

Originally named protoactinium, the name of Element 91 was changed to protactinium (Pa), whose longest-lived isotope has an atomic mass of 231. Shiny and malleable, protactinium has a melting point of 2,861.6°F (1,572°C). It is highly toxic, and so rare that no commercial uses have been found for it. Indeed, protactinium could only be produced from the decay products of uranium and radium, and thus it is one of the few elements with an atomic number less than 93 that cannot be said to occur in nature.

## URANIUM

**URANIUM'S EARLY HISTORY.** Chemistry books, in fact, differ as to the number of naturally occurring elements. Some say 88, which is the most correct figure, because protactinium, along with technetium (43) and two others, cannot be said to appear naturally on Earth. Other books say 92, a less accurate figure that nonetheless reflects an indisputable fact: above uranium (U, 92) on the periodic table, there are no elements that generally occur in nature. (However, a few do occur as radioactive by-products of uranium.)

But uranium is much more than just the last truly natural element, though for about a century it apparently had no greater importance. When German chemist Martin Heinrich Klaproth (1743-1817) discovered it in 1789, he named it after another recent discovery: the planet Uranus. During the next 107 years, uranium had a very quiet existence, befitting a rather dull-looking material.

Though it is silvery white when freshly cut, uranium soon develops a thin coating of black uranium oxide, which turns it a flat gray. Yet glassmakers did at least manage to find a use for it—as a coating for decorative glass, to which it imparted a hazy, fluorescent yellowish green hue. Little did they know that they were using one of the most potentially dangerous substances on Earth.

**THE DESTRUCTIVE POWER OF URANIUM.** In 1895, German physicist Wilhelm Röntgen (1845-1923) noticed that photographic plates held near a Crookes tube—a device for analyzing electromagnetic radiation—became fogged. He dubbed the rays that had caused this x rays. A year later, in 1896, French physicist Henri Becquerel (1852-1908) left some photographic plates in a drawer with a sample of uranium, and discovered that the uranium likewise caused a fogging of the photographic plates. This meant that uranium was radioactive.

With the development of nuclear fission by Hahn and German chemist Fritz Strassman in 1938, uranium suddenly became all-important because of its ability to undergo nuclear fission, accompanied by the release of huge amounts of energy. During World War II, in what was known as the Manhattan Project, a team of scientists in Los Alamos, New Mexico, developed the atomic



Gloved hands hold a gray lump of uranium. This material has been remolded after having been removed from a Titan II Missile, part of the disarmament after the end of the Cold War. *(Martin Marietta; Roger Ressmeyer/Corbis. Reproduced by permission.)*

bomb. The first of the two atomic bombs dropped on Japan in 1945 contained uranium, while the second contained the transuranium element plutonium.

**OTHER USES FOR URANIUM.** Though nuclear weapons have fortunately not been used against human beings since 1945, uranium has remained an important component of

nuclear energy—both in the development of bombs and in the peaceful application of nuclear power. It has other uses as well, due to the fact that it is extremely dense.

Indeed, uranium has a density close to that of gold and platinum, but is much cheaper, because it is more abundant on Earth. In addition, various isotopes of uranium are a by-product of nuclear power, which separates these isotopes from the highly fissionable $^{235}U$ isotope. Thus, quantities of uranium are available for use in situations where a great deal of mass is required in a small space: in counterweights for aircraft control systems, for instance, or as ballast for missile reentry vehicles.

Because $^{238}U$ has a very long half-life—$4.47 \cdot 10^9$ years, or approximately the age of Earth—it is used to estimate the age of rocks and other geological features. Uranium-238 is the "parent" of a series of "daughter" isotopes that geologists find in uranium ores. Uranium-235 also produces "daughter" isotopes, including isotopes of radium, radon, and other radioactive series. Eventually, uranium isotopes turn into lead, but this can take a very long time: even $^{235}U$, which lasts for a much shorter period than $^{238}U$, has a half-life of about 700 million years.

The radiation associated with various isotopes of uranium, as well as other radioactive materials, is extremely harmful. It can cause all manner of diseases and birth defects, and is potentially fatal. The tiny amounts of radiation produced by uranium in old pieces of decorative glass is probably not enough to cause any real harm, but the radioactive fallout from Hiroshima resulted in birth defects among the Japanese population during the late 1940s.

## Transuranium Elements

Transuranium elements are those elements with atomic numbers higher than that of uranium. None of these occur in nature, except as isotopes that develop in trace amounts in uranium ore. The first such element was neptunium (Np, 93), created in 1940 by American physicist Edwin Mattison McMillan (1907-1991) and American physical chemist Philip Hauge Abelson.

The development of the cyclotron by American physicist Ernest Lawrence (1901-1958) at the University of California at Berkeley in the 1930s made possible the artificial creation of new elements. A cyclotron speeds up protons or ions (charged atoms) and shoots them at atoms of uranium or other elements with the aim of adding positive charges to the nucleus. In the first two decades after the use of the cyclotron to create neptunium, scientists were able to develop eight more elements, all the way up to mendelevium (Md, 101), named in honor of the man who created the periodic table.

Most of these efforts occurred at Berkeley under the leadership of American nuclear chemist Glenn T. Seaborg (1912-1999) and American physicist Albert Ghiorso. The pace of development in transuranium elements slowed after about 1955, however, primarily due to the need for ever more powerful cyclotrons and ion-accelerating machines. In addition to Berkeley, there are two other centers for studying these high-energy elements: the Joint Institute for Nuclear Research in Dubna, Russia, and the Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, Germany.

## The Transuranium Actinides

**PLUTONIUM.** Just as neptunium had been named for the next planet beyond Uranus, a second transuranium element, discovered by Seaborg and two colleagues in 1940, was named after Pluto. Among the isotopes of plutonium (Pu, 94) is plutonium-239, one of the few fissionable isotopes other than uranium-233 and uranium-235. For that reason, it was applied in the second bomb dropped on Japan.

In addition to its application in nuclear weapons, plutonium is used in nuclear power reactors, and in thermoelectric generators, which convert the heat energy it releases into electricity. Plutonium is also used as a power source in artificial heart pacemakers. Huge amounts of the element are produced each year as a by-product of nuclear power reactors.

**BERKELEY DISCOVERIES OF THE 1950S.** Because the lanthanide element above it on the periodic table was named europium after Europe, americium (Am, 95) was named after America. Discovered by Seaborg, Ghiorso, and two others in 1944, it was first produced in a nuclear reaction involving plutonium-239. Americium radiation is used in measuring the thickness of glass during production; in addition, the isotope americium-241 is used as an ionization source in smoke detectors, and

## KEY TERMS

**ACTINIDES:** Those elements that fill the 5f orbital. Because actinium—which does not fill the 5f orbital—exhibits characteristics similar to those of the actinides, it is usually considered part of the actinides family. Of the other 14 actinides, usually shown at the bottom of the periodic table, only the first three occur in nature.

**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 of elements in order of atomic number.

**ELECTRON CLOUD:** A term used to describe the pattern formed by orbitals.

**HALF-LIFE:** The length of time it takes a substance to diminish to one-half its initial amount. For a sample of radioisotopes, the half-life is the amount of time it takes for half of the nuclei to become stable isotopes. Half-life can be a few seconds; on the other hand, for uranium-238, it is a matter of several billion years.

**INNER TRANSITION METALS:** The lanthanides and actinides, which are unique in that they fill the f orbitals. For this reason, they are usually treated separately.

**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. Isotopes may be either stable or unstable. The unstable type, known as radioisotopes, are radioactive.

**LANTHANIDES:** The transition metals that fill the 4f orbital.

**MASS NUMBER:** The sum of protons and neutrons in the atom's nucleus. The designation $^{238}U$, for uranium-238, means that this particular isotope of uranium has a mass number of 238. Since uranium has an atomic number of 92, this means that uranium-238 has 146 neutrons in its nucleus.

**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. The plural of "nucleus" is nuclei.

**ORBITAL:** A region of probabilities regarding the position of an electron for an atom in a particular energy state. The higher the principal energy level, the more complex the pattern of orbitals.

in portable devices for taking gamma-ray photographs.

Above curium (Cm, 96) on the periodic table is the lanthanide gadolinium, named after Finnish chemist Johan Gadolin (1760-1852). Therefore, the discoverers of Element 96 also decided to name it after a person, Marie Curie. As with some of the other relatively low-number transuranium elements, this one is not entirely artificial: its most stable isotope, some geologists believe, may have been present in rocks many millions of years ago, but these isotopes have long since decayed. Because curium generates great amounts of energy as it decays, it is used for providing compact sources of power in remote locations on Earth and in space vehicles.

## KEY TERMS CONTINUED

**PRINCIPAL ENERGY LEVEL:** A value indicating the distance that an electron may move away from the nucleus of an atom. This is designated by a whole-number integer, beginning with 1 and moving upward. The higher the principal energy level, the greater the energy in the atom, and the more complex the pattern of orbitals. Elements in the transition metal family have principal energy levels of 4, 5, 6, or 7.

**RADIATION:** In a general sense, radiation can refer to anything that travels in a stream, whether that stream be composed of subatomic particles or electromagnetic waves. In a more specific sense, the term relates to the radiation from radioactive materials, which can be harmful to human beings.

**RADIOACTIVITY:** A term describing a phenomenon whereby certain isotopes, known as radioisotopes, are subject to a form of decay brought about by the emission of high-energy particles. "Decay" does not mean that the isotope "rots"; rather, it decays to form another isotope until eventually (though this may take a long time) it becomes stable.

**RADIOISOTOPE:** An isotope subject to the decay associated with radioactivity. A radioisotope is thus an unstable isotope.

**SUBLEVEL:** A region within the principal energy level occupied by electrons in an atom. Whatever the number n of the principal energy level, there are n sublevels. Actinides are distinguished by the fact that their valence electrons are in a sublevel corresponding to the 5f orbital.

**TRANSITION METALS:** A group of 40 elements (counting lanthanum and actinium), which are the only elements that fill the d orbital. In addition, the transition metals have their valence electrons on two different principal energy levels. Though the lanthanides and actinides are considered inner transition metals, they are usually considered separately.

**TRANSURANIUM ELEMENTS:** Elements with an atomic number higher than that of uranium (92). These have all have been produced artificially. The transuranium elements include 11 actinides, as well as 9 transition metals.

**VALENCE ELECTRONS:** Electrons that occupy the highest principal energy level in an atom. These are the electrons involved in chemical bonding.

When Seaborg, Ghiorso, and others created Element 97, berkelium (Bk), they again took the naming of lanthanides as their cue. Just as terbium, directly above it on the periodic table, had been named for the Swedish town of Ytterby, where so many lanthanides were discovered, they named the new element after the American city where so many transuranium elements had been developed. Berkelium has no known applications outside of research. The Berkeley team likewise named californium (Cf, 98) after the state where Berkeley is located. Researchers today are studying the use of californium radiation for treatment of tumors involved in various forms of cancer.

**THE REMAINING TRANSURANIUM ACTINIDES.** The remaining transura-

nium actinides were all named after famous people: einsteinium (Es, 99) for Albert Einstein (1879-1955); fermium (Fm, 100) after Italian-American physicist Enrico Fermi (1901-1954); mendelevium after Mendeleev; nobelium (No, 102) after Swedish inventor and philanthropist Alfred Nobel (1833-1896); and lawrencium (Lr, 103) after Ernest Lawrence.

Both einsteinium and fermium were by-products of nuclear testing at Bikini Atoll in the south Pacific in 1952. For this reason, their existence was kept a secret for two years. Neither element has a known application. The same is true of mendelevium, produced by Seaborg, Ghiorso, and others with a cyclotron at Berkeley in 1955, as well as the other two transuranium actinides.

## Beyond the Transuranium Actinides

As noted earlier, there are nine additional transuranium elements, which properly belong to the transition metals. The first of these is rutherfordium, discovered in 1964 by the Dubna team and named after Ernest Rutherford (1871-1937), the British physicist who discovered the nucleus. The Dubna team named dubnium, discovered in 1967, after their city, just as berkelium had been named after the Berkeley team's city. Both groups developed versions of Element 106 in 1974, and both agreed to name it seaborgium after Seaborg, but this resulted in a controversy that was not settled for some time.

The name of bohrium, created at Dubna in 1976, honors Danish physicist Niels Bohr (1885-1962), who developed much of the model of electron energy levels discussed earlier in this essay. Hassium, produced at the GSI in 1984, is named for the German state of Hess. Two years earlier, the GSI team also created the last named element on the periodic table, meitnerium (109), named after Meitner. Beyond meitnerium are three elements, as yet unnamed, created at the GSI in the mid-1990s.

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# LANTHANIDES

## CONCEPT

Along the bottom of the periodic table of elements, separated from the main body of the chart, are two rows, the first of which represents the lanthanides. Composed of lanthanum and the 14 elements of the lanthanide series, the lanthanides were once called the "rare earth" metals. In fact, they are not particularly rare: many of them appear in as much abundance as more familiar elements such as mercury. They are, however, difficult to extract, a characteristic that defines them as much as their silvery color; sometimes high levels of reactivity; and sensitivity to contamination. Though some lanthanides have limited uses, members of this group are found in everything from cigarette lighters to TV screens, and from colored glass to control rods in nuclear reactors.

## HOW IT WORKS

### Defining the Lanthanides

The lanthanide series consists of the 14 elements, with atomic numbers 58 through 71, that follow lanthanum on the periodic table of elements. These 14, along with the actinides—atomic numbers 90 through 103—are set aside from the periodic table due to similarities in properties that define each group.

Specifically, the lanthanides and actinides are the only elements that fill the f-orbitals. The lanthanides and actinides are actually "branches" of the larger family known as transition metals. The latter appear in groups 3 through 12 on the IUPAC version of the periodic table, though they are not numbered on the North American version.

The lanthanide series is usually combined with lanthanum, which has an atomic number of 57, under the general heading of lanthanides. As their name indicates, members of the lanthanide series share certain characteristics with lanthanum; hence the collective term "lanthanides." These 15 elements, along with their chemical symbols, are:

- Lanthanum (La)
- Cerium (Ce)
- Praseodymium (Pr)
- Neodymium (Nd)
- Promethium (Pm)
- Samarium (Sm)
- Europium (Eu)
- Gadolinium (Gd)
- Terbium (Tb)
- Dysprosium (Dy)
- Holmium (Ho)
- Erbium (Er)
- Thulium (Tm)
- Ytterbium (Yb)
- Lutetium (Lu)

Most of these are discussed individually in this essay.

**PROPERTIES OF LANTHANIDES.** Bright and silvery in appearance, many of the lanthanides—though they are metals—are so soft they can be cut with a knife. Lanthanum, cerium, praseodymium, neodymium, and europium are highly reactive. When exposed to oxygen, they form an oxide coating. (An oxide is a compound formed by metal with an oxygen.) To prevent this result, which tarnishes the



Misch metal, which includes cerium, is often used in cigarette lighters. *(Massimo Listri/Corbis. Reproduced by permission.)*

metal, these five lanthanides are kept stored in mineral oil.

The reactive tendencies of the other lanthanides vary: for instance, gadolinium and lutetium do not oxidize until they have been exposed to air for a very long time. Nonetheless, lanthanides tend to be rather "temperamental" as a class. If contaminated with other metals, such as calcium, they corrode easily, and if contaminated with nonmetals, such as nitrogen or oxygen, they become brittle. Contamination also alters their boiling points, which range from 1,506.2°F (819°C) for ytterbium to 3,025.4°F (1,663°C) for lutetium.

Lanthanides react rapidly with hot water, or more slowly with cold water, to form hydrogen gas. As noted earlier, they also are quite reactive with oxygen, and they experience combustion readily in air. When a lanthanide reacts with another element to form a compound, it usually loses three of its outer electrons to form what are called tripositive ions, or atoms with an electric charge of +3. This is the most stable ion for lanthanides, which sometimes develop less stable +2 or +4 ions. Lanthanides tend to form ionic compounds, or compounds containing either positive or negative ions, with other substances—in particular, fluorine.

## Are They Really "Rare"?

Though they were once known as the rare earth metals, lanthanides were so termed because, as we shall see, they are difficult to extract from compounds containing other substances—including other lanthanides. As for rarity, the scarcest of the lanthanides, thulium, is more abundant than either arsenic or mercury, and certainly no one thinks of those as rare substances. In terms of parts per million (ppm), thulium has a presence in Earth's crust equivalent to 0.2 ppm. The most plentiful of the lanthanides, cerium, has an abundance of 46 ppm, greater than that of tin.

If, on the other hand, rarity is understood not in terms of scarcity, but with regard to difficulty in obtaining an element in its pure form, then indeed the lanthanides are rare. Because their properties are so similar, and because they are inclined to congregate in the same substances, the original isolation and identification of the lanthanides was an arduous task that took well over a century. The progress followed a common pattern.

First, a chemist identified a new lanthanide; then a few years later, another scientist came along and extracted another lanthanide from the

sample that the first chemist had believed to be a single element. In this way, the lanthanides emerged over time, each from the one before it, rather like Russian matryoshka or "nesting" dolls.

**EXTRACTING LANTHANIDES.** Though most of the lanthanides were first isolated in Scandinavia, today they are found in considerably warmer latitudes: Brazil, India, Australia, South Africa, and the United States. The principal source of lanthanides is monazite, a heavy, dark sand from which about 50% of the lanthanide mass available to science and industry has been extracted.

In order to separate lanthanides from other elements, they are actually combined with other substances—substances having a low solubility, or tendency to dissolve. Oxalates and fluorides are low-solubility substances favored for this purpose. Once they are separated from non-lanthanide elements, ion exchange is used to separate one lanthanide element from another.

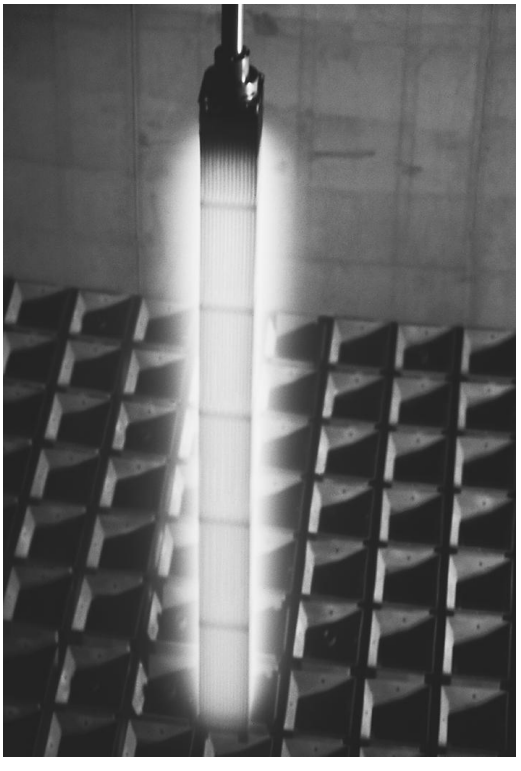
There is a pronounced decrease in the radii of lanthanide atoms as they increase in atomic number: in other words, the higher the atomic number, the smaller the radius. This decrease, known as the lanthanide contraction, aids in the process of separation by ion exchange. The lanthanides are mixed in an ionic solution, then passed down a long column containing a resin. Various lanthanide ions bond more or less tightly, depending on their relative size, with the resin.

After this step, the lanthanides are washed out of the ion exchange column and into various solutions. One by one, they become fully separated, and are then mixed with acid and heated to form an oxide. The oxide is then converted to a fluoride or chloride, which can then be reduced to metallic form with the aid of calcium.

## REAL-LIFE APPLICATIONS

### The Historical Approach

In studying the lanthanides, one can simply move along the periodic table, from lanthanum all the way to lutetium. However, in light of the difficulties involved in extracting the lanthanides, one from another, an approach along historical lines aids in understanding the unique place each lanthanide occupies in the overall family.



SAMARIUM IS USED IN NUCLEAR POWER PLANT CONTROL RODS, SUCH AS THE ONE SHOWN HERE. *(Tim Wright/Corbis. Reproduced by permission.)*

The terms "lanthanide series" or even "lanthanides" did not emerge for some time—in other words, scientists did not immediately know that they were dealing with a whole group of metals. As is often the case with scientific discovery, the isolation of lanthanides followed an irregular pattern, and they did not emerge in order of atomic number.

Cerium was in fact discovered long before lanthanum itself, in the latter half of the eighteenth century. There followed, a few decades later, the discovery of a mineral called ytterite, named after the town of Ytterby, Sweden, near which it was found in 1787. During the next century, most of the remaining lanthanides were extracted from ytterite, and the man most responsible for this was Swedish chemist Carl Gustav Mosander (1797-1858).

Because Mosander had more to do with the identification of the lanthanides than any one individual, the middle portion of this historical overview is devoted to his findings. The recognition and isolation of lanthanides did not stop with Mosander, however; therefore another

group of minerals is discussed in the context of the latter period of lanthanide discovery.

## Early Lanthanides

**cerium.** In 1751, Swedish chemist Axel Crönstedt (1722-1765) described what he thought was a new form of tungsten, which he had found at the Bastnäs Mine near Riddarhyttan, Sweden. Later, German chemist Martin Heinrich Klaproth (1743-1817) and Swedish chemist Wilhelm Hisinger (1766-1852) independently analyzed the material Crönstedt had discovered, and both concluded that this must be a new element. It was named cerium in honor of Ceres, an asteroid between Mars and Jupiter discovered in 1801. Not until 1875 was cerium actually extracted from an ore.

Among the applications for cerium is an alloy called misch metal, prepared by fusing the chlorides of cerium, lanthanum, neodymium, and praseodymium. The resulting alloy ignites at or below room temperature, and is often used as the "flint" in a cigarette lighter, because it sparks when friction from a metal wheel is applied.

Cerium is also used in jet engine parts, as a catalyst in making ammonia, and as an antiknock agent in gasoline—that is, a chemical that reduces the "knocking" sounds sometimes produced in an engine by inferior grades of fuel. In cerium (IV) oxide, or $CeO_2$, it is used to extract the color from formerly colored glass, and is also applied in enamel and ceramic coatings.

**gadolinium.** In 1794, seven years after the discovery of ytterite, Finnish chemist Johan Gadolin (1760-1852) concluded that ytterite contained a new element, which was later named gadolinite in his honor. A very similar name would be applied to an element extracted from ytterite, and the years between Gadolin's discovery and the identification of this element spanned the period of the most fruitful activity in lanthanide identification.

During the next century, all the other lanthanides were discovered within the composition of gadolinite; then, in 1880, Swiss chemist Jean-Charles Galissard de Marignac (1817-1894) found yet another element hiding in it. French chemist Paul Emile Lecoq de Boisbaudran (1838-1912) rediscovered the same element six years later, and proposed that it be called gadolinium.

Silvery in color, but with a sometimes yellowish cast, gadolinium has a high tendency to oxidize in dry air. Because it is highly efficient for capturing neutrons, it could be useful in nuclear power reactors. However, two of its seven isotopes are in such low abundance that it has had little nuclear application. Used in phosphors for color television sets, among other things, gadolinium shows some promise for ultra high-tech applications: at very low temperatures it becomes highly magnetic, and may function as a superconductor.

## Mosander's Lanthanides

**lanthanum.** Between 1839 and 1848, Mosander was consumed with extracting various lanthanides from ytterite, which by then had come to be known as gadolinite. When he first succeeded in extracting an element, he named it lanthana, meaning "hidden." The material, eventually referred to as lanthanum, was not prepared in pure form until 1923.

Like a number of other lanthanides, lanthanum is very soft—so soft it can be cut with a knife—and silvery-white in color. Among the most reactive of the lanthanides, it decomposes rapidly in hot water, but more slowly in cold water. Lanthanum also reacts readily with oxygen, and corrodes quickly in moist air.

As with cerium, lanthanum is used in misch metal. Because lanthanum compounds bring about special optical qualities in glass, it also used for the manufacture of specialized lenses. In addition, compounds of lanthanum with fluorine or oxygen are used in making carbon-arc lamps for the motion picture industry.

**samarium.** While analyzing an oxide formed from lanthanide in 1841, Mosander decided that he had a new element on his hands, which he called didymium. Four decades later, Boisbaudran took another look at didynium, and concluded that it was not an element; rather, it contained an element, which he named samarium after the mineral samarskite, in which it is found. Still later, Marignac was studying samarskite when he discovered what came to be known as gadolinium. But the story did not end there: even later, in 1901, French chemist Eugène-Anatole Demarçay (1852-1903) found yet another element, europium, in samarskite.

Samarium is applied today in nuclear power plant control rods, in carbon-arc lamps, and in

optical masers and lasers. In alloys with cobalt, it is used in manufacturing the most permanent electromagnets available. Samarium is also utilized in the manufacture of optical glass, and as a catalyst in the production of ethyl alcohol.

**ERBIUM AND TERBIUM.** To return to Mosander, he was examining ytterite in 1843 when he identified three different "earths," all of which he also named after Ytterby: yttria, erbia, and terbia. Erbium was the first to be extracted. A pure sample of its oxide was prepared in 1905 by French chemist Georges Urbain (1872-1938) and American chemist Charles James (1880-1928), but the pure metal itself was only extracted in 1934.

Soft and malleable, with a lustrous silvery color, erbium produces salts (which are usually combinations of a metal with a nonmetal) that are pink and rose, making it useful as a tinting agent. One of its oxides is utilized, for instance, to tint glass and porcelain with a pinkish cast. It is also applied, to a limited extent, in the nuclear power industry.

Mosander also identified another element, terbium, in ytterite in 1839, and Marignac isolated it in a purer form nearly half a century later, in 1886. To repeat a common theme, it is silvery-gray and soft enough to be cut with a knife. When hit by an electron beam, a compound containing terbium emits a greenish color, and thus it is used as a phosphor in color television sets.

## Later Isolation of Lanthanides

**YTTERBIUM, HOLMIUM, AND THULIUM.** For many years after Mosander, there was little progress in the discovery of lanthanides, and when it came, it was in the form of a third element, named after the town where so many of the lanthanides were discovered. In 1878, while analyzing what Mosander had called erbia, Marignac realized that it contained one or possibly two elements.

A year later, Swedish chemist Lars Frederik Nilson (1840-1899) concluded that it did indeed contain two elements, which were named ytterbium and scandium. (Scandium, with an atomic number of 21, is not part of the lanthanide series.) Urbain is sometimes credited for discovering ytterbium: in 1907, he showed that the materials Nilson had studied were actually a mixture of two oxides. In any case, Urbain said that

## KEY TERMS

**ALLOY:** A mixture of two or more metals.

**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 of elements in order of atomic number.

**ION:** An atom or atoms that has lost or gained one or more electrons, and thus has a net electrical charge.

**LANTHANIDE CONTRACTION:** A progressive decrease in the radius of lanthanide atoms as they increase in atomic number.

**LANTHANIDE SERIES:** A group of 14 elements, with atomic numbers 58 through 71, that follow lanthanum on the periodic table of elements.

**LANTHANIDES:** The lanthanide series, along with lanthanum.

**OXIDE:** A compound formed by the chemical bonding of a metal with oxygen.

**PERIODIC TABLE OF ELEMENTS:** A chart showing the elements arranged in order of atomic number, grouping them according to common characteristics.

**RARE EARTH METALS:** An old name for the lanthanides, reflecting the difficulty of separating them from compounds containing other lanthanides or other substances.

**TRANSITION METALS:** Groups 3 through 12 on the IUPAC or European version of the periodic table of elements. The lanthanides and actinides, which appear at the bottom of the periodic table, are "branches" of this family.

the credit should be given to Marignac, who is the most important figure in the history of lanthanides other than Mosander. As for ytterbium, it is highly malleable, like other lanthanides, but does not have any significant applications in industry.

Swedish chemist Per Teodor Cleve (1840-1905) found in 1879 that erbia contained two more elements, which he named holmium and thulium. Thulium refers to the ancient name for Scandinavia, Thule. Rarest of all the lanthanides, thulium is highly malleable—and also highly expensive. Hence it has few commercial applications.

**DYSPROSIUM.** Named for the Greek word *dysprositos*, or "hard to get at," dysprosium was discovered by Boisbaudran. Separating ytterite in 1886, he found gallium (atomic number 31—not a lanthanide); samarium (discussed above); and dysprosium. Yet again, a mineral extracted from ytterite had been named after a previously discovered element, and, yet again, it turned out to contain several elements. The substance in question this time was holmium, which, as Boisbaudran discovered, was actually a complex mixture of terbium, erbium, holmium, and the element he had identified as dysprosium. A pure sample was not obtained until 1950.

Because dysprosium has a high affinity for neutrons, it is sometimes used in control rods for nuclear reactors, "soaking up" neutrons rather as a sponge soaks up water. Soft, with a lustrous silver color like other lanthanides, dysprosium is also applied in lasers, but otherwise it has few uses.

**EUROPIUM AND LUTETIUM.** Whereas many other lanthanides are named for regions in northern Europe, the name for europium refers to the European continent as a whole, and that of lutetium is a reference to the old Roman name for Paris. As mentioned earlier, Demarçay found europium in samarskite, a discovery he made in 1901. Actually, Boisbaudran had noticed what appeared to be a new element about a decade previously, but he did not pursue it, and thus the credit goes to his countryman.

Most reactive of the lanthanides, europium responds both to cold water and to air. In addition, it is capable of catching fire spontaneously. Among the most efficient elements for the capture of neutrons, it is applied in the control systems of nuclear reactors. In addition, its compounds are utilized in the manufacture of phosphors for TV sets: one such compound, for instance, emits a reddish glow. Yet another europium compound is added to the glue on postage stamps, making possible the electronic scanning of stamps.

Urbain, who discovered lutetium, named it after his hometown. James also identified a form of the lanthanide, but did not announce his discovery until much later. Except for some uses at a catalyst in the production of petroleum, lutetium has few industrial applications.

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# NONMETALS AND METALLOIDS

NONMETALS
METALLOIDS
HALOGENS
NOBLE GASES
CARBON
HYDROGEN

# NONMETALS

## CONCEPT

Nonmetals, as their name implies, are elements that display properties quite different from those of metals. Generally, they are poor conductors of heat and electricity, and they are not ductile: in other words, they cannot be easily reshaped. Included in this broad grouping are the six noble gases, the five halogens, and eight "orphan" elements. Two of these eight—hydrogen and carbon—are so important that separate essays are devoted to them. Two more, addressed in this essay, are absolutely essential to human life: oxygen and nitrogen. Hydrogen and helium, a nonmetal of the noble gas family, together account for about 99% of the mass of the universe, while Earth and the human body are composed primarily of oxygen, with important components of carbon, nitrogen, and hydrogen. Indeed, much of life—human, animal, and plant—can be summed up with these four elements, which together make Earth different from any other known planet. Among the other "orphan" nonmetals are phosphorus and sulfur, the "brimstone" of the Bible, as well as boron and selenium.

## HOW IT WORKS

### Defining the Nonmetals

The majority of elements on the periodic table are metals: solids (along with one liquid, mercury) which are lustrous or shiny in appearance. Metals are ductile, or malleable, meaning that they can be molded into different shapes without breaking. They are excellent conductors of heat and electricity, and tend to form positive ions by losing electrons. The vast majority of elements—87 in all—are metals, and these occupy the left, center, and part of the right-hand side of the periodic table.

With the exception of hydrogen, placed in Group 1 above the alkali metals, the nonmetals fill a triangle-shaped space in the upper right corner of the periodic table. All gaseous elements are nonmetals, a group that also includes some solids, as well as bromine, the only element other than mercury that is liquid at room temperature. In general, the nonmetals are characterized by properties opposite those of metals. They are poor conductors of heat and electricity (though carbon, a good electrical conductor, is an exception), and they tend to form negative ions by gaining electrons. They are not particularly malleable, and whereas most metals are shiny, nonmetals may be dull-colored, black (in the case of carbon in some forms or allotropes), or invisible, as is the case with most of the gaseous nonmetals.

### Grouping the Nonmetals

Whereas the metals can be broken down into five families, along with seven "orphans"—elements that do not fit into a family grouping—the nonmetals are arranged in two families, as well as eight "orphans." Hydrogen, because of its great abundance in the universe and its importance to chemical studies, is addressed in a separate essay within this book. The same is true of carbon: though not nearly as abundant as hydrogen, carbon is a common element of all living things, and therefore it is discussed in the essay on Carbons and Organic Chemistry.




Liquid nitrogen accounts for about one-third of all commercial uses of nitrogen. Here, a medical worker puts a sample of bone marrow into a tank of liquid nitrogen for preservation. *(Leif Skoogfors/ Corbis. Reproduced by permission.)*

The other six "orphan" nonmetals, which will be examined in detail later in this essay, are listed below by atomic number:

- 5. Boron (B)
- 7. Nitrogen (N)
- 8. Oxygen (O)
- 15. Phosphorus (P)
- 16. Sulfur (S)
- 34. Selenium (Se)

**THE NOBLE GASES.** The noble gases, discussed in detail within an essay devoted to that subject, are listed below by atomic number:

- 2. Helium (He)
- 10. Neon (Ne)
- 18. Argon (Ar)
- 36. Krypton (Kr)
- 54. Xenon (Xe)
- 86. Radon (Rn)

Occupying Group 8 of the North American periodic table, the noble gases—with the exception of helium—have valence electron configurations of $ns^2np^6$. This means that they have two valence electrons (the electrons involved in chemical bonding) on the orbital designated as s, and six more on the p orbital. As for n, this designates the energy level, a number that corresponds to the period or row that an element occupies on the periodic table.

Most elements bond according to what is known as the octet rule, forming a shell composed of eight electrons. Since the noble gases already have eight electrons on their shell, they tend not to bond with other elements: hence the name "noble," which in this context means "set apart." Helium, on the other hand, has a valence shell of $s^2$; however, it too is characterized by a lack of reactivity, and therefore is included in the noble gas family. Noble gases are all monatomic, meaning that they exist as individual atoms, rather than in molecules. To put it another way, their molecules are single atoms. (By contrast, atoms of oxygen, for instance, usually combine to form a diatomic molecule, designated $O_2$.)

Due to their apparent lack of reactivity, the noble gases—also known as the rare gases—were once called the inert (inactive) gases. Indeed, helium, neon, and argon have not been found to combine with other elements to form compounds. However, in 1962, English chemist Neil Bartlett (1932-) succeeded in preparing a compound of xenon with platinum and fluorine ($XePtF_6$), thus overturning the idea that the




AT AN "OXYGEN BAR," YOU CAN RELAX BY BREATHING OXYGEN. HERE, A WOMAN IS BREATHING FLAVORED OXYGEN AT A BAR IN JAPAN. *(AFP/Corbis. Reproduced by permission.)*

noble gases were entirely "inert." Since that time, numerous compounds of xenon with other elements, most notably oxygen and fluorine, have been developed. Fluorine has also been used to form simple compounds with krypton and radon.

**THE HALOGENS.** Next to the noble gases, in Group 7, are the halogens, a family discussed in a separate essay. These are listed below, along with atomic number and chemical symbol. Note that astatine is sometimes included with the metalloids, elements that display characteristics both of metals and nonmetals.

- 9. Fluorine (F)
- 17. Chlorine (Cl)
- 35. Bromine (Br)
- 53. Iodine (I)
- 85. Astatine (At)

The halogens all have valence electron configurations of $ns^2np^5$: in other words, at any energy level n, they have two valence electrons in the s orbital, and 5 in the p orbital. In terms of phase of matter, the halogens are the most varied family on the periodic table. Fluorine and chlorine are gases, iodine is a solid, and bromine (as noted earlier) is one of only two elements existing at room temperature as a liquid. As for astatine, it is a solid too, but so highly radioactive it is hard to determine much about its properties. (The only other nonmetal that has a large number of radioactive isotopes is the noble gas radon, considered highly dangerous.)

Though they are "next door" to the noble gases, the halogens could not be more different. Whereas their neighbors to the right are the least reactive elements on the periodic table, the halogens are the most reactive. Indeed, fluorine has the highest possible value of electronegativity, the relative ability of an atom to attract valence electrons. It is therefore one of the only elements that will bond with a noble gas.

All of the halogens tend to form salts, compounds—formed, along with water, from the reaction of an acid and base—that bring together a metal and a nonmetal. Due to this tendency, the first of the family to be isolated—chlorine, in 1811—was originally named "halogen," a combination of the Greek words halos, or salt, and gennan, "to form or generate." In their pure form, halogens are diatomic, and in contact with other elements, they form ionic bonds, which are the strongest form of chemical bond. In the process of bonding, they become negatively charged ions, or anions.

### Abundance of the Nonmetals

**IN THE UNIVERSE.** As is stated many times throughout this book, humans may be created equal, but the elements are not. Though 88 elements exist in nature, this certainly does not mean that each occupies a 1/88 share of the total pie. Just two elements—the nonmetals hydrogen and helium, which occupy the first two positions on the periodic table—account for 99.9% of the matter in the entire universe, yet the percentage of matter they make up on Earth is very small.

The reason for this disparity is that, whereas our own planet (as far as we know) is unique in sustaining life—requiring oxygen, carbon, nitrogen, and other elements—the vast majority of the universe is made up of stars, composed primarily of hydrogen and helium.

**ON EARTH AND IN THE ATMOSPHERE.** Nonmetals account for a large portion of Earth's total known elemental mass—that is, the composition of the planet's crust, waters, and atmosphere. Listed below are figures ranking nonmetals within the overall picture of elements on Earth. The numbers following each element's name indicate the percentage of each within the planet's total known elemental mass.

- 1. Oxygen (49.2%)
- 9. Hydrogen (0.87%)
- 11. Chlorine (0.19%)
- 12. Phosphorus (0.11%)
- 14. Carbon (0.08%)
- 15. Sulfur (0.06%)
- 17. Nitrogen (0.03%)
- 18. Fluorine (0.03%)

Some of the figures above may seem rather small, but in fact only 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. In Earth's atmosphere, the composition is all nonmetallic, as one might expect:

- 1. Nitrogen (78%)
- 2. Oxygen (21%)
- 3. Argon (0.93%)
- 4. Various trace gases, including water vapor, carbon dioxide, and ozone or $O_3$ (0.07%)

**IN THE HUMAN BODY.** As noted earlier, carbon is a component in all living things, and it constitutes the second-most abundant element in the human body. Together with oxygen and hydrogen, it accounts for 93% of the body's mass. Listed below are the most abundant nonmetals in the human body, by ranking.

- 1. Oxygen (65%)
- 2. Carbon (18%)
- 3. Hydrogen (10%)
- 4. Nitrogen (3%)
- 6. Phosphorus (1.0%)
- 9. Sulfur (0.26%)
- 11. Chlorine (0.14%)

## REAL-LIFE APPLICATIONS

### Boron

The first "orphan" nonmetal, by atomic number, is boron, named after the Arabic word buraq or the Persian burah. (It is thus unusual in being one of the only elements whose name is not based on a word from a European language, or—for the later elements—the name of a person or place.) It was discovered in 1808 by English chemist Sir Humphry Davy (1778-1829), a man responsible for identifying or isolating numerous elements; French physicist and chemist Joseph Gay-Lussac (1778-1850), known in part for the gas law named after him; and French chemist Louis Jacques Thénard (1777-1857). These scientists used the reaction of boric acid ($H_3BO_3$) with potassium to isolate the element.

Sometimes classified as a metalloid because it is a semiconductor of electricity, boron is applied in filaments used in fiber optics research. Few of its other applications, however, have much to do with electrical conductivity. Boric or boracic acid is used as a mild antiseptic, and in North America, it is applied for the control of cockroaches, silverfish, and other pests. A compound known as borax is a water softener in washing powders, while other compounds are used to produce enamels for the coating of refrigerators and other appliances. Compounds involving boron are also present in pyrotechnic flares, because they emit a distinctive green color, and in the igniters of rockets.

### Nitrogen

Though most people think of air as consisting primarily of oxygen, in fact—as noted above—the greater part of the air we breathe is made up

of nitrogen. Scottish chemist David Rutherford (1749-1819) is usually given credit for discovering the element: in 1772, he identified nitrogen as the element that remained when oxygen was removed from air. Several other scientists around 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). When air is cooled to -328°F (-200°C) 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 can also be obtained from compounds such as potassium nitrate or saltpeter, found primarily in India; or sodium nitrate (Chilean saltpeter), which comes from the desert regions of Chile. To isolate nitrogen, various processes are undertaken in a laboratory—for instance, heating barium azide or sodium azide, both of which contain nitrogen.

**REACTIONS WITH OTHER ELEMENTS.** Existing as diatomic molecules, nitrogen forms very strong triple bonds, and as a result tends to be fairly unreactive at low temperatures. Thus, for instance, when a substance burns, it reacts with the oxygen in the air, but not with the nitrogen. At high temperatures, however, nitrogen combines with other elements, reacting with metals to form nitrides; with hydrogen to form ammonia; with $O_2$ to form nitrites; and with $O_3$ to form nitrates.

Nitrogen and oxygen, in particular, react at high temperatures to form numerous compounds: nitric oxide (NO), nitrous oxide ($N_2O$), nitrogen dioxide ($NO_2$), dinitrogen trioxide ($N_2O_3$), and dinitrogen pentoxide ($N_2O_5$). In reaction with halogens, nitrogen forms unstable, explosive compounds such as nitrogen trifluoride ($NF_3$), nitrogen trichloride ($NCl_3$), and nitrogen triiodide ($NI_3$). One thing is for sure: never mix ammonia with bleach, which involves the halogen chlorine. Together, these two produce chloramines, gases with poisonous vapors.

**USES FOR NITROGEN.** One of the most striking scenes in a memorable film, "Terminator 2: Judgment Day" (1991), occurs near the end of the movie, when the villainous T-1000 robot steps into a pool of liquid nitrogen and cracks to pieces. As noted, nitrogen must be at extremely low temperatures to assume liquid form. Liquid nitrogen, which accounts for about one-third of all commercial uses of the element, is applied for quick-freezing foods, and for preserving foods in transit. Liquid nitrogen also makes it possible to process materials, such as some forms of rubber, that are too pliable for machining at room temperature. These materials are first cooled in liquid nitrogen, and then become more rigid.

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 detrimentally affected by oxidation. Because it is far less combustible than air (magnesium is one of the few elements that burns nitrogen in combustion), nitrogen is also 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.

**NITROGEN, THE ENVIRONMENT, AND HEALTH.** The nitrogen cycle is the process whereby nitrogen passes from the atmosphere into living things, and ultimately back into the atmosphere. Both through the action of lightning in the sky, and of bacteria in the soil, nitrogen is converted to nitrates and nitrites—compounds of nitrogen and oxygen. These are then absorbed by plants to form plant proteins, which convert to animal proteins in the bodies of animals who eat the plants. When an animal dies, the proteins are returned to the soil, and denitrifying bacteria break down these compounds, returning elemental nitrogen to the atmosphere.

Not all nitrogen in the atmosphere is healthful, however. Oxides of nitrogen, formed in the high temperatures of internal combustion

engines, pass into the air as nitric oxide. This compound reacts readily with oxygen in the air to form nitrogen dioxide, a toxic reddish-brown gas that adds to the tan color of smog over major cities.

Another health concern is posed by sodium nitrate and sodium nitrite, added to bacon, sausage, hot dogs, ham, bologna and other food products to inhibit the growth of harmful microorganisms. Many researchers believe that nitrites impair the ability of a young child's blood to carry oxygen. Furthermore, nitrites often combine with amines, a form of organic compound, to create a variety of toxins known as nitrosoamines. Because of concerns about these dangers, scientists and health activists have called for a ban on the use of nitrites and nitrates as food additives.

## OXYGEN

Discovered independently by Swedish chemist Carl W. Scheele (1742-1786) and English chemist Joseph Priestley (1733-1804) in the period 1773-1774, oxygen was named by a third scientist, French chemist Antoine Lavoisier (1743-1794). Believing (incorrectly) that all acids contained the newly discovered element, Lavoisier called it oxygen, which comes from a French word meaning "acid-former."

Like many elements, oxygen has been in use since the beginning of time. But this is quite different from saying, for instance, that iron has been in use since the early stages of human history. A person can live without iron (except for the necessary quantities in the human body), and can survive for weeks or even months without food. One can live for a few days without water (the most famous and plentiful of all oxygen-containing compounds); but one cannot survive for more than a few minutes without the oxygen in air.

Oxygen appears in three allotropes (different versions of the same element, distinguished by molecular structure): monatomic oxygen (O); diatomic oxygen or $O_2$; and triatomic oxygen ($O_3$), better known as ozone. The diatomic form dominates the natural world, but in the upper atmosphere, ozone forms a protective layer that keeps the Sun's harmful ultraviolet radiation from reaching Earth. Concerns that chlorofluorocarbons (CFCs) may be depleting the ozone layer by converting these triatomic molecules to $O_2$ has led to a reduction in the output of CFCs by industrialized nations.

**OBTAINING OXYGEN.** Oxygen, of course, is literally "in the air," mixed with larger quantities of nitrogen. Higher up in the atmosphere, it occurs as a free element. Through electrolysis,, it can be obtained from water; however, this process is prohibitively expensive for most commercial applications.

Oxygen-containing compounds are also sources of oxygen for commercial use, but generally oxygen is obtained by the fractional distillation of liquid air, described above with regard to nitrogen. After the nitrogen has been separated, argon and neon (which also have lower boiling points than oxygen) also boil off, leaving behind an impure form of oxygen. This is further purified by a process of cooling, liquefying, and evaporation, which eliminates traces of noble gases such as krypton and xenon.

Many millions of years ago, when Earth was first formed, there was no oxygen on the planet. The growth of oxygen on Earth coincided with the development of organisms that, as they evolved, increasingly needed oxygen. The present concentration of oxygen in the atmosphere, oceans, and the rocks of Earth's crust was reached about 580 million years ago, and is sustained today by biological activity. When plants undergo photosynthesis, carbon dioxide and water react in the presence of chlorophyll to produce carbohydrates and oxygen.

**OXIDES AND OTHER COMPOUNDS.** Though the bond in diatomic oxygen is strong, once it is broken, monatomic oxygen reacts readily with other elements to form a seemingly limitless range of compounds: oxides, silicates, carbonates, phosphates, sulfates, and other more complex substances.

The process known as oxidation results in the formation of numerous oxides. Sometimes oxygen and another element form several oxides, as for example in the case of nitrogen, whose five oxides are listed above. Water is an oxide; so too are carbon dioxide and carbon monoxide. When animals and plants die, the organic materials that make them up react with oxygen in the air, resulting in a complex form of oxidation known as decay—or, in common language, "rotting."

Oxygen, reacting with compounds such as hydrocarbons, produces carbon dioxide and water vapor at high temperatures. If the oxida-

tion process is extremely rapid, and takes place at high temperatures, it is usually identified as combustion. In addition, oxygen reacts with iron and other metals to form oxides. Many of these oxides, commonly known as rust, are undesirable.

Every year, millions upon millions of dollars are spent on painting metal structures, or for other precautions to protect against the formation of metallic oxides. On the other hand, metallic oxides may be produced deliberately for applications in materials such as mortar color, to enhance the appearance of a brick building.

**USES OF OXYGEN.** Aside from the obvious application of oxygen for breathing, there are four major fields that make use of this element: medicine, metallurgy, rocketry, and the field of chemistry concerned with chemical synthesis. The medical application is closest to how we normally use oxygen in our daily lives. In oxygen therapy, a patient having difficulty breathing is given doses of pure, or nearly pure, oxygen. This is used during surgical procedures, and to treat patients who have had heart attacks, as well as those suffering from various infectious or respiratory diseases.

The use of oxygen in metallurgy involves refining coke, which is almost pure carbon, to make carbon monoxide. Carbon monoxide, in turn, reduces iron oxides to pure metallic iron. Oxygen is also used in blast furnaces to convert pig iron to steel by removing excess carbon, silicon, and metallic impurities. In addition, oxygen is applied in torches for welding and cutting. In the form of liquefied oxygen, or LOX, oxygen is used in rockets and missiles. The space shuttle, for instance, carries a huge internal tank containing oxygen and hydrogen, which, when they react, give the vehicle enormous thrust.

In chemical synthesis—the preparation of compounds (especially organic ones) from easily available chemicals—commercial chemists use oxygen, for instance, to loosen the bonds in hydrocarbons. If this is done too quickly, it results in combustion; but at a controlled rate, the chemical synthesis of hydrocarbons can generate products such as acetylene, ethylene, and propylene.

Oxygen can be used to produce synthetic fuels, as well as for water purification and sewage treatment. Airplanes carry oxygen supplies in case of depressurization at high altitudes; in addition, divers carry tanks in which oxygen is mixed with helium, rather than nitrogen, to prevent the dangerous condition known as "the bends."

As early as the 1960s, smog-ridden cities such as Tokyo and Mexico City were equipped with coin-operated oxygen booths—a sort of "phone booth for the lungs." After inserting the appropriate amount of money, a person received a dose of oxygen for inhaling. This idea, spawned by necessity, is the likely inspiration for a rather bizarre fad that took hold in the trendier cities of North America during the mid-1990s: oxygen bars. Popular in Los Angeles, New York, and Toronto, these are establishments in which patrons pay up to a dollar per minute to inhale pure or flavored oxygen. Enthusiasts have touted the health benefits of this practice, but some physicians have warned of oxygen toxicity and other dangers.

## THE OTHER "ORPHAN" NONMETALS

**PHOSPHORUS.** Some elements, such as iron or gold, were known from ancient or even prehistoric times—meaning that the identity of the discoverer is unknown. Phosphorus was the first element whose discoverer is known: German chemist Hennig Brand (c. 1630-c. 1692), who identified it in 1674.

Highly reactive with oxygen, phosphorus is used in the production of safety matches, smoke bombs, and other incendiary devices. It is also important in fertilizers, and in various industrial applications. Phosphorus forms a number of important compounds, most notably phosphates, on which animals and plants depend.

Phosphorus pollution, created by the use of household detergents containing phosphates, raised environmental concerns in the 1960s and 1970s. It was feared that high phosphate levels in rivers and creeks would lead to runaway, detrimental growth of plants and algae near bodies of water, a condition known as eutrophication. These concerns led to a ban on the use of phosphates in detergents.

**SULFUR.** On its own, sulfur has no smell, but in combination with other elements, it often acquires a foul odor, which has given it an unpleasant reputation. The element's smell, combined with its combustibility, led to the associa-

## KEY TERMS

**ALLOTROPES:** Different versions of the same element, distinguished by molecular structure.

**DIATOMIC:** A term describing an element that exists as molecules composed of two atoms. This is in contrast to monatomic elements.

**ELECTROLYSIS:** The use of an electric current to cause a chemical reaction.

**HALOGENS:** Group 7 of the periodic table of elements, with valence electron configurations of $ns^2np^5$. In contrast to the noble gases, the halogens are known for high levels of reactivity.

**ION:** An atom or group of atoms 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. Isotopes may be either stable or unstable. The unstable type, known as radioisotopes, are radioactive.

**METALS:** Elements that are lustrous or shiny in appearance; malleable, meaning that they can be molded into different shapes without breaking; and excellent conductors of heat and electricity. Metals, which constitute the vast majority of all elements, tend to form positive ions by losing electrons.

**MONATOMIC:** A term describing an element that exists as single atoms. This in contrast to diatomic elements.

**NOBLE GASES:** Group 8 of the periodic table of elements, all of whom (with the exception of helium) have valence electron configurations of $ns^2np^6$. The noble gases are noted for their extreme lack of reactivity—in other words, they tend not to react to, or bond with, other elements.

**NONMETALS:** Elements that have a dull appearance; are not malleable; are poor conductors of heat and electricity; and tend to gain electrons to form negative ions. They are thus opposite of metals in most regards, as befits their name. In addition to hydrogen, in Group 1 of the periodic table, the other 18 nonmetals occupy the upper right-hand side of the chart. They include the noble gases, halogens, and seven "orphan" elements: boron, carbon, nitrogen, oxygen, phosphorus, sulfur, and selenium.

**ORBITAL:** A pattern of probabilities regarding the position of an electron for an atom in a particular energy state. The higher the principal energy level, the more complex the pattern of orbitals.

**RADIOACTIVITY:** A term describing a phenomenon whereby certain isotopes known as radioisotopes are subject to a form of decay brought about by the emission of high-energy particles. "Decay" does not mean that the isotope "rots"; rather, it decays to form another isotope until eventually (though this may take a long time), it becomes stable.

**REACTIVITY:** The tendency for bonds between atoms or molecules to be made or broken in such a way that materials are transformed.

**SHELL:** The orbital pattern of the valence electrons at the outside of an atom.

**VALENCE ELECTRONS:** Electrons that occupy the highest principal energy level in an atom. These are the electrons involved in chemical bonding.

tion of "brimstone"—the ancient name for sulfur—with the fires of hell.

Because it is not usually combined with other elements in nature, the discovery of sulfur was relatively easy. Pure, or nearly pure, sulfur is mined on the Gulf Coast of the United States, as well as in Poland and Sicily. Sulfur compounds also appear in a number of ores, such as gypsum (calcium sulfate), or magnesium sulfate, better known as Epsom salts.

Applications of the aforementioned compounds are discussed in the Alkaline Earth Metals essay. In addition, sulfates are used as agricultural insecticides, and for killing algae in water supplies. Potassium aluminum sulfate, a gelatinous solid that sinks to the bottom when dropped into water, is also used in water purification. Sulfur is sometimes applied in pure form as a fungicide, or in matches, fireworks, and gunpowder. More often, however, it is found in compounds such as the sulfates or the sulfides—including sulfuric acid and the evil-smelling gas known as hydrogen sulfide.

Rotten eggs and intestinal gas are two examples of hydrogen sulfide, which, though poisonous, usually poses little danger, because the smell keeps people away. Another sulfur compound is mercaptan, an ingredient in the skunk's distinctive aroma. Tiny quantities of mercaptan are added to natural gas (which has no odor) so that dangerous gas leaks can be detected by smell.

**SELENIUM.** When Swedish chemist Jons Berzelius (1779-1848) first discovered selenium in 1817, in deposits at the bottom of a tank in a sulfuric acid factory, he thought it was tellurium, a metalloid discovered in 1800. A few months later, he reconsidered the evidence, and realized he had found a new element. Because tellurium, which lies just below selenium on the periodic table, had been named for the Earth (*tellus* in Latin), he named his new discovery after the Greek word for the Moon, *selene*.

Found primarily in impurities from sulfide ores, selenium is often obtained commercially as a by-product of the refining of copper by electrolysis. It occurs in at least three allotropic forms, variously black and red in color. Plants and animals, including humans, need small amounts of selenium to survive, but larger quantities can be toxic. This was demonstrated in the late 1970s, when waterfowl in the area of Kesterson Reservoir in northern California began turning up with birth defects. The cause was later traced to the dumping of selenium from agricultural wastes and industrial plants.

Because selenium is photovoltaic (able to convert light directly into electricity) and photoconductive (meaning that its resistance to the flow of electric current decreases in the presence of light), it has applications in photocells, exposure meters, and solar cells. It is also used for the conversion of alternating current to direct current, and is applied as a semiconductor in electronic and solid-state appliances. Photocopiers use selenium in toners, and compounds containing selenium are used to tint glass red, orange, or pink.

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# METALLOIDS

## CONCEPT

The term "metalloid" may sound like a reference to a heavy-metal music fan, but in fact it describes a small collection of elements on the right-hand side of the periodic table. Forming a diagonal between boron and astatine, which lies four rows down and four columns to the right of boron, the metalloids are six elements that display qualities of both metals and nonmetals. (Some classifications include boron and astatine as well, but in this book, they are treated as a nonmetal and a halogen respectively.) Of these six—silicon, germanium, arsenic, antimony, tellurium, and polonium—only a few are household names. People know that arsenic is poison, and they have some general sense that silicon is important in surgical implants. But most people do not know that silicon, also the principal material in sand and glass, is the second-most plentiful element on Earth. Without silicon, from which computer chips are made, our computer-based society simply could not exist.

## HOW IT WORKS

### Families and "Orphans"

Most elements fit into some sort of "family" grouping: the alkali metals, the alkaline earth metals, transition metals, lanthanides, actinides, halogens, and noble gases. These seven families, five metallic and two nonmetallic, account for 91 of 112 elements on the periodic table.

The "orphan" elements, or those not readily classifiable within a family, occupy groups 3 through 6 on the North American version of the periodic table, which only numbers the "tall" columns.

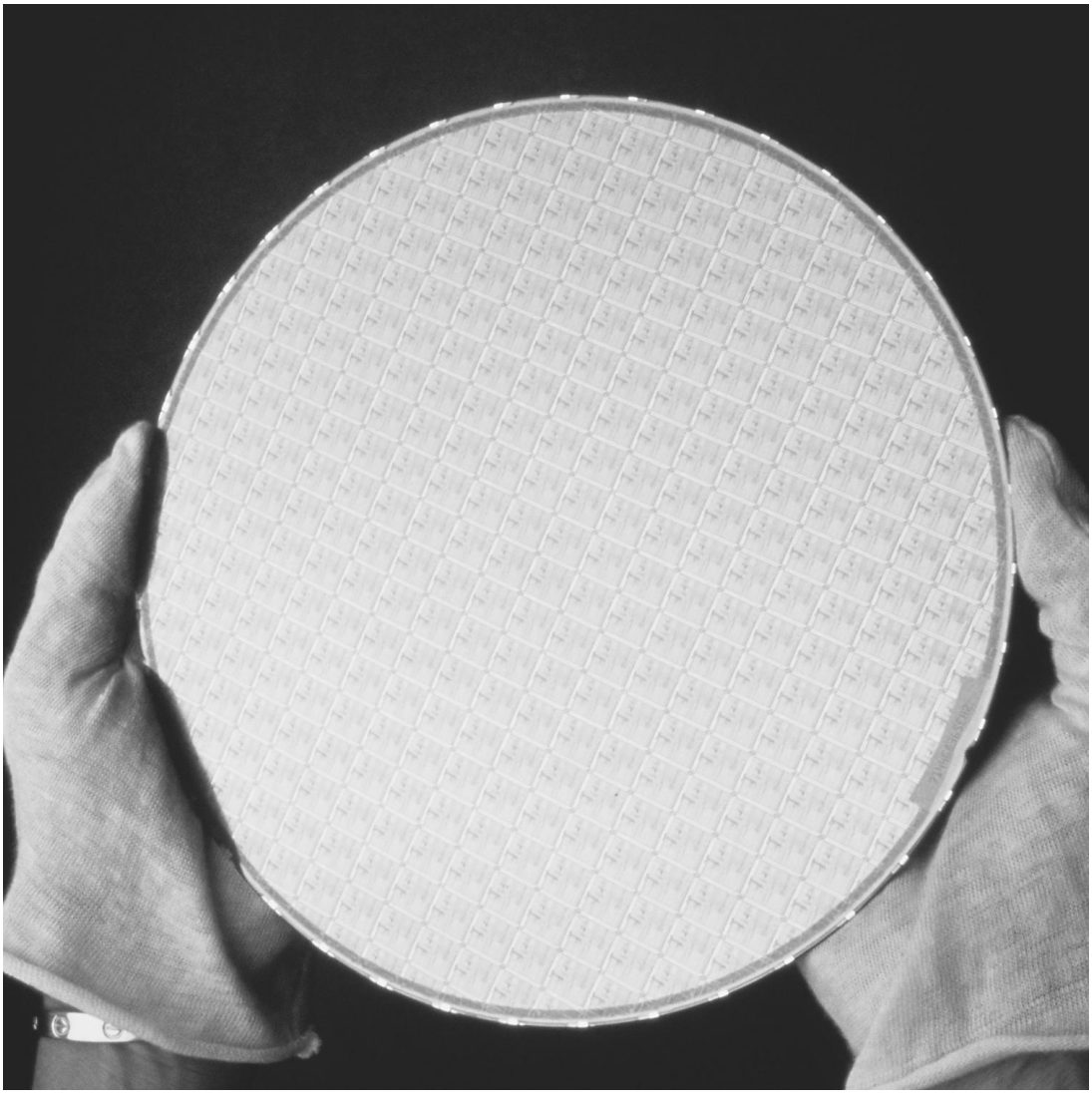
Twenty elements, occupying a rectangle that stretches across four groups or columns, and five periods or rows, are "orphans." (This is in addition to hydrogen, on Period 1, Group 1.) These are best classified, not by family, but by cross-family characteristics that unite large groups of elements. These cross-family groupings can be likened to nations: on one level, a person identifies with his or her family ("I'm a Smith"); but on another level, a person has a national identity ("I'm an American.")

Likewise gold, for instance, is both a member of the transition metals family, and of the larger metals grouping. The "orphan" elements, because they have no family, are best identified with characteristics that unite a large body of elements. (For this reason, the "orphan" metals are discussed in the Metals essay, and the "orphan" nonmetals in the Nonmetals essay.)

### Between Metals and Nonmetals

Of the twenty "orphan" elements in groups 3 through 6, seven are metals and seven nonmetals. Between them runs a diagonal, comprising the six metalloids. (As noted earlier, boron is sometimes considered a metalloid, but in this book, it is discussed in the Nonmetals essay, while astatine—also sometimes grouped with the metalloids—is treated in the Halogens essay.) What is a metalloid? The best way to answer that question is by evaluating the differences between a metal and a nonmetal.

On the periodic table, metals fill the left, center, and part of the right-hand side of the



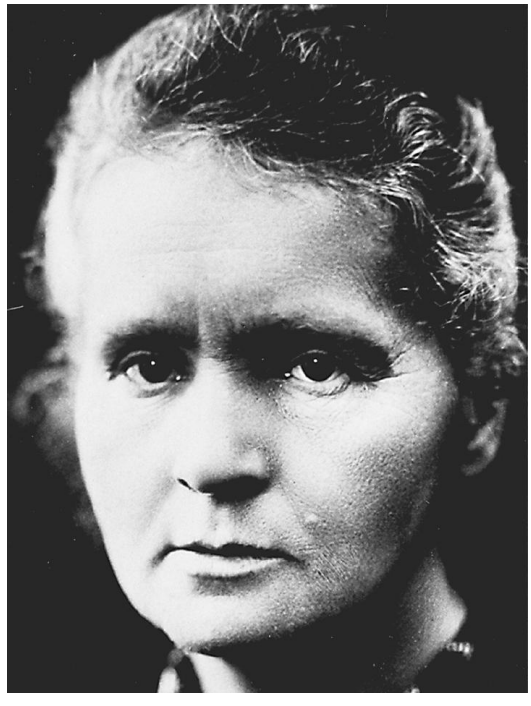
WITHOUT SILICON, FROM WHICH COMPUTER CHIPS ARE MADE, OUR COMPUTER-BASED SOCIETY SIMPLY COULD NOT EXIST. HERE, A WORKER HOLDS A SILICON WAFER WITH INTEGRATED CIRCUITS. *(Charles O'Rear/Corbis. Reproduced by permission.)*

chart, as well as the two rows—corresponding to the lanthanides and actinides—placed separately at the bottom. Thus it should not come as a surprise that most elements (87, in fact) are metals. Metals are lustrous or shiny in appearance, and ductile, meaning that they can be molded into different shapes without breaking. They are excellent conductors of heat and electricity, and tend to form positive ions by losing electrons.

Nonmetals, which occupy the upper right-hand side of the periodic table, include the noble gases, halogens, and the seven "orphan" elements alluded to above. With the addition of hydrogen (which, as noted, is covered in a separate essay), they comprise 19 elements. Whereas all metals are solids, except for mercury—a liquid at room temperature—the nonmetals are a collection of gases, solids, and one other liquid, bromine. (Not surprisingly, all gaseous elements are nonmetals.) As their name suggests, nonmetals are opposite to metals in most regards: dull in appearance, they are not particularly ductile or malleable. With the exception of carbon, they are poor conductors of heat and electricity, and tend to gain electrons to form negative ions.

## SURVEY OF THE METALLOIDS

The metalloids can thus be defined as those elements which exhibit characteristics of both metals and nonmetals. They are all solids, but not



POLONIUM WAS FIRST ISOLATED BY MARIE AND PIERRE CURIE. MARIE CURIE NAMED THE ELEMENT IN HONOR OF HER HOMELAND, POLAND.

lustrous, and conduct heat and electricity moderately well.

The six metalloids treated here are listed below, with the atomic number and chemical symbol of each.

- 14. Silicon (Si)
- 32. Germanium (Ge)
- 33. Arsenic (As)
- 51. Antimony (Sb)
- 52. Tellurium (Te)
- 84. Polonium (Po)

Silicon is the second most abundant element on Earth, comprising 25.7% of the planet's known elemental mass. Together with oxygen, it accounts for nearly three-quarters of the known total. (The planet's core is probably composed largely of iron, with significant deposits of uranium and other metals between the crust and the core, but geologists can only make educated guesses as to the elemental composition beneath the crust.)

**THE METALLOIDS IN HISTORY.** By far the most important of the metalloids, silicon has been in use as a compound for centuries, but was only isolated in the early nineteenth century. Arsenic and antimony were likewise known from ancient times, and both attracted the attention of alchemists—medieval mystics, in many regards the forerunners of chemists, who believed it was possible to change plain metals into gold.

Traces of the alchemical mindset remained a part of European science as late as the mid-eighteenth century, a tendency exemplified by the fact that tellurium, discovered around that time, was believed to be "unripe gold." On the other hand, the discovery of germanium more than a century later—following predictions of its existence based on the periodic table—reflected a much greater degree of scientific rigor. Finally, the isolation of polonium, known for its radioactivity, was evidence of an even more advanced stage of development in chemistry and science as a whole.

## REAL-LIFE APPLICATIONS

### SILICON

Swedish chemist Jons Berzelius (1779-1848) discovered silicon in 1823, but humans had been using the element—in the form of compounds known as silicates—for thousands of years. Indeed, silicon may have been one of the first elements formed, many millions of years before life appeared on this planet. Geologists believe that the Earth was once composed primarily of molten iron, oxygen, silicon, and aluminum, still the predominant elements in the planet's crust. Because iron has a greater atomic mass, it settled toward the center, while the more lightweight elements rose to the surface.

Silicon is found in everything from the Sun and other stars, as well as meteorites, to plants and animal bones. Many hundreds of minerals on Earth contain silicon and oxygen in various forms: for instance, silicon and oxygen form silica ($SiO_2$), commonly known as sand. This sand is mixed with lime and soda (sodium carbonate), as well other substances, to make glass. The purest varieties of silica form quartz, known for its clear crystals, while impure quartz forms crystals of semiprecious gems such as amethyst, opal, and agate.

**COMPOUNDS: SILICATES AND SILICONES.** Silicon is directly below carbon on the periodic table, and the elements in

that group (which includes germanium, selenium, and lead) are sometimes called the "carbon family." Like carbon, silicon forms a huge array of compounds, because it has four electrons to share in chemical bonding, and thus can form long strings of atoms. Because silicon atoms are much larger than carbon atoms, however, not as many other atoms can get close to silicon. Thus the number of possible compounds involving silicon—though still quite impressive—is less than the many millions of carbon-based compounds

Often silicon is combined with oxygen in long chains that use the oxygen atoms as separators. Because oxygen has a valence of two, meaning that it can bond to two other atoms at a time, it bonds easily between two other silicon atoms. The silicon, meanwhile, has two other electrons to use in bonding, so it typically attaches to two more, non-bridging, oxygen atoms. Compounds of this type are known as silicates, and most of the rocks and clay on Earth—with the exception of lime, which is calcium oxide—are silicates made up of combinations of silicon, oxygen, and various metals such as aluminum, iron, sodium, and potassium.

Silicones are another variety of compound involving silicon atoms strung together by bridging oxygen atoms. Instead of attaching to two other, non-bridging oxygen atoms, as in a silicate, the silicon atoms in a silicone attach to organic groups—that is, molecules containing carbon. Because silicones often resemble organic compounds such as oils, greases, and rubber, silicone oils are frequently used in place of organic petroleum as a lubricant because they can withstand greater variations in temperature. Silicone rubbers are used in everything from bouncing balls to space vehicles. And because the body tolerates the introduction of silicone implants better than it does organic ones, silicones are used in surgical implants as well.

**THE MANY OTHER USES OF SILICON.** Silicones are also present in electrical insulators, rust preventives, fabric softeners, hair sprays, hand creams, furniture and automobile polishes, paints, adhesives (including bathtub sealers), and chewing gum. Yet even this list does not exhaust the many applications of elemental silicon, as opposed to silicone.

Due to its semi-metallic qualities, silicon is used as a semiconductor of electricity. Computer chips are tiny slices of ultra-pure 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, in order 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.

## ARSENIC

Silicon is unquestionably the "star" of the metalloids, but several other elements in this broad grouping have been known since ancient times. Among these is arsenic, well-known from many a detective novel. Highly poisonous, it is often a fixture of such stories: in a typical plot, a greedy nephew drops some arsenic into the tea of an elderly aunt who has left money to him in her will, and it is up to the detective/hero/heroine to uncover the details behind this dastardly scheme. The use of arsenic as a prop in such tales had already become something of a cliché by 1941, when "Arsenic and Old Lace," a play by Joseph Kesselring that satirized an old-fashioned "whodunit," made its debut on Broadway.

Known since ancient times, arsenic is named after the Greek word *arsenikon*, meaning "yellow orpiment." (Orpiment is arsenic trisulfide, or $As_2S_3$.) But the Greeks were not the only peoples in antiquity who knew of arsenic and its toxic properties: the Egyptians and Chinese were likewise familiar with it. Alchemists took an interest in arsenic, and one of them, Albertus Magnus (1193-1280)—a German physician who contributed significantly to the rebirth of interest in science during the late Middle Ages—probably isolated the element from arsenic trisulfide in about 1250.

Arsenic is more than just a prop in a detective story. (And in fact it is not a very effective poison for a murderer who hopes to get away with his crime: traces of arsenic remain in the body of a murder victim—even in the person's hair—for years after death.) Today, arsenic is

used for purposes such as bronzing, and for hardening and improving the sphericity (roundness) of lead shot in shotgun shells.

In solid-state devices such as transistors, arsenic or antimony is used for the purposes of "doping." This may sound like another version of the whodunit-style poisoning described above, but actually doping involves the alteration of chemical properties by deliberately introducing impurities. Through the doping of silicon, its electrical conductivity is improved.

## Antimony

In ancient times, antimony was known by the Latin name *stibium*; hence its chemical symbol of Sb. The word, which can be deciphered as "a metal that does not occur by itself," has roots much older than the Roman civilization, however. Many centuries before the rise of the Romans, the biblical prophet Jeremiah railed against women's use of "stibic stone" to paint their faces. In fact, stibic stone is antimony (III) sulfide, or $Sb_2S_3$, a black mineral which has long been used as an eyeliner.

During the Middle Ages, alchemists studied *antimony* and its compounds, but the first scientist to distinguish between the compounds and the element itself was French chemist Jean-Baptiste Buquet, in 1771. During the early modern era, antimony was used in making bells, tools, and type for printing presses, because its addition to an alloy strengthened the other metals. Today, antimony is added to lead in storage batteries to make the lead harder and stronger. It is still used in metal type, as well as bullets and cable sheathing.

Antimony was a component in early varieties of matches, but by 1855, the less volatile phosphorus had replaced it. In altered form, however, antimony still appears in some matches. Oxides and sulfides of antimony are also applied in paints, ceramics, fireworks, pharmaceuticals, and other products. These are also utilized for dyeing cloth and fireproofing materials. In addition, as noted above with regard to arsenic, antimony is applied for the doping of silicon and other materials in semiconductors, particularly those that use infrared detectors.

## Tellurium

When Hungarian chemist Joseph Ramacsaházy first described tellurium in the mid-eighteenth century, he did so in alchemical terms, referring to it as "unripe gold." This reflected the belief, still lingering from the Middle Ages, that metals "grow" to higher states. At least part of his confusion is understandable, since the element did appear in minerals that also contained gold.

A few years later, Baron Franz Joseph Müller von Reichenstein, an Austrian mining inspector in Transylvania, analyzed the substance, which he concluded was bismuth sulfide. Later he changed his mind, then subjected the material to a series of tests over a period of many years, until finally he sent a sample to the distinguished German chemist, Martin Heinrich Klaproth (1743-1817). Klaproth concluded that it was indeed a new element, and suggested the Latin word tellus, for "earth," as a name.

Grayish-white and lustrous, tellurium looks like a metal, but it is much more brittle than most metallic elements. Furthermore, it is a semiconductor, which further separates it from the typically conductive metals. Its semiconductive properties have led to applications in building electronic components. Added to copper and stainless steel, tellurium improves the machinability of those metals; in addition, tellurium compounds are used for the coloring of glass, porcelain, enamel, and ceramics.

## Germanium and Polonium

Germanium. Both named after European countries, germanium and polonium were identified much later than the other metalloids. In 1871, two years after he created his famous periodic table, Russian chemist Dmitri Ivanovitch Mendeleev (1834-1907) predicted the existence of an element he called "eka-silicon." This turned out to be germanium, which sits directly beneath silicon on the periodic table, and which was discovered in 1886 by German chemist Clemens Alexander Winkler (1838-1904).

Germanium is principally used as a doping agent in making transistor elements. It is also used as a phosphor in fluorescent lamps. In addition, germanium and germanium oxide, transparent to the infrared portion of the electromagnetic spectrum, are present in infrared spectroscopes and infrared detectors.

**POLONIUM.** While the applications of germanium are limited compared to those of, say, silicon, polonium is useful primarily as a source

## KEY TERMS

**ION:** An atom or group of atoms 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. Isotopes may be either stable or unstable. The latter type, known as radioisotopes, are radioactive.

**METALLOIDS:** Elements which exhibit characteristics of both metals and nonmetals. Metalloids are all solids, but are not lustrous or shiny, and they conduct heat and electricity moderately well. The six metalloids occupy a diagonal region between the metals and nonmetals on the right side of the periodic table. Sometimes boron and astatine are included with the metalloids, but in this volume, they are treated as an "orphan" nonmetal and a halogen, respectively.

**METALS:** Elements that are lustrous, or shiny in appearance, and malleable, meaning that they can be molded into different shapes without breaking. They are excellent conductors of heat and electricity, and tend to form positive ions by losing electrons.

**NONMETALS:** Elements that have a dull appearance; are not malleable; are poor conductors of heat and electricity; and tend to gain electrons to form negative ions. They are thus the opposite of metals in most regards, as befits their name.

**NORTH AMERICAN SYSTEM:** A version of the periodic table of elements that only numbers groups of elements in which the number of valence electrons equals the group number—that is, the two "tall" columns to the left of the transition metals, as well as the six "tall" columns to the right.

**"ORPHAN":** An element that does not belong to any clearly defined family of elements. The metalloids are all "orphans."

**RADIOACTIVITY:** A term describing a phenomenon whereby certain isotopes known as radioisotopes are subject to a form of decay brought about by the emission of high-energy particles. "Decay" does not mean that the isotope "rots"; rather, it decays to form another isotope until eventually (though this may take a long time) it becomes stable.

of neutrons in atomic laboratories—hardly something with which a person comes in contact during the course of an ordinary day. Yet the isolation of polonium by Polish-French physicist and chemist Marie Curie (1867-1934), along with her husband Pierre (1859-1906), a French physicist, was a prelude to one of the greatest stories in the history of chemistry.

Setting out to find radioactive elements other than uranium, the Curies refined a large quantity of pitchblende, an ore commonly found in uranium mines. Within a year, they had discovered polonium, which Marie named after her homeland. Polonium is about 100 times as radioactive as uranium, but the Curies were certain that yet another element lay in the pitchblende, and they devoted the next four years to the exhausting process of isolating it. The story of radium, its isolation, and the great price Marie Curie paid for working with radioactive materials is discussed in the essay on Alkaline Earth Metals.

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# HALOGENS

## CONCEPT

Table salt, bleach, fluoride in toothpaste, chlorine in swimming pools—what do all of these have in common? Add halogen lamps to the list, and the answer becomes more clear: all involve one or more of the halogens, which form Group 7 of the periodic table of elements. Known collectively by a term derived from a Greek word meaning "salt-producing," the halogen family consists of five elements: fluorine, chlorine, bromine, iodine, and astatine. The first four of these are widely used, often in combination; the last, on the other hand, is a highly radioactive and extremely rare substance. The applications of halogens are many and varied, including some that are dangerous, controversial, and deadly.

## HOW IT WORKS

### The Halogens on the Periodic Table

As noted, the halogens form Group 7 of the periodic table of elements. They are listed below, along with chemical symbol and atomic number:

- Fluorine (F) 9
- Chlorine (Cl): 17
- Bromine (Br): 35
- Iodine (I): 53
- Astatine (At): 85

On the periodic table, as displayed in chemistry labs around the world, the number of columns and rows does not vary, since these configurations are the result of specific and interrelated properties among the elements. There are always 18 columns; however, the way in which these are labeled differs somewhat from place to place. Many chemists outside the United States refer to these as 18 different groups of elements; however, within the United States, a somewhat different system is used.

In many American versions of the chart, there are only eight groups, sometimes designated with Roman numerals. The 40 transition metals in the center are not designated by group number, nor are the lanthanides and actinides, which are set apart at the bottom of the periodic table. The remaining eight columns are the only ones assigned group numbers. In many ways, this is less useful than the system of 18 group numbers; however, it does have one advantage.

**ELECTRON CONFIGURATIONS AND BONDING.** In the eight-group system, group number designates the number of valence electrons. The valence electrons, which occupy the highest energy levels of an atom, are the electrons that bond one element to another. These are often referred to as the "outer shell" of an atom, though the actual structure is much more complex. In any case, electron configuration is one of the ways halogens can be defined: all have seven valence electrons.

Because the rows in the periodic table indicate increasing energy levels, energy levels rise as one moves up the list of halogens. Fluorine, on row 2, has a valence-shell configuration of $2s^2 2p^5$; while that of chlorine is $3s^2 3p^5$. Note that only the energy level changes, but not the electron configuration at the highest energy level. The same goes for bromine ($4s^2 4p^5$), iodine ($4s^2 4p^5$), and astatine ($5s^2 5p^5$).

All members of the halogen family have the same valence-shell electron configurations, and thus tend to bond in much the same way. As we



Salt, like the mound shown here, is a safe and common substance that contains chlorine. *(Charles O'Rear/Corbis. Reproduced by permission.)*

shall see, they are inclined to form bonds more readily than most other substances, and indeed fluorine is the most reactive of all elements.

Thus it is ironic that they are "next door" to the Group 8 noble gases, the least reactive among the elements. The reason for this, as discussed in the Chemical Bonding essay, is that most elements bond in such a way that they develop a valence shell of eight electrons; the noble gases are already there, so they do not bond, except in some cases—and then principally with fluorine.

## Characteristics of the Halogens

In terms of the phase of matter in which they are normally found, the halogens are a varied group. Fluorine and chlorine are gases, iodine is a solid, and bromine is one of only two elements that exists at room temperature as a liquid. As for astatine, it is a solid too, but so highly radioactive that it is hard to know much about its properties.

Despite these differences, the halogens have much in common, and not just with regard to their seven valence electrons. Indeed, they were identified as a group possessing similar characteristics long before chemists had any way of knowing about electrons, let alone electron configurations. One of the first things scientists noticed about these five elements is the fact that they tend to form salts. In everyday terminology, "salt" refers only to a few variations on the same thing—table salt, sea salt, and the like. In chemistry, however, the meaning is much broader: a salt is defined as the result of bonding between an acid and a base.

Many salts are formed by the bonding of a metal and a nonmetal. The halogens are all nonmetals, and tend to form salts with metals, as in the example of sodium chloride (NaCl), a bond between chlorine, a halogen, and the metal sodium. The result, of course, is what people commonly call "salt." Due to its tendency to form salts, the first of the halogens to be isolated—chlorine, in 1811—was originally named "halogen." This is a combination of the Greek words *halos*, or salt, and *gennan*, "to form or generate."

In their pure form, halogens are diatomic, meaning that they exist as molecules with two atoms: $F_2$, $Cl_2$, and so on. When bonding with metals, they form ionic bonds, which are the strongest form of chemical bond. In the process, halogens become negatively charged ions, or anions. These are represented by the symbols F-, Cl-, Br-, and I-, as well as the names fluoride, chloride, bromide, and iodide. All of the halogens

are highly reactive, and will combine directly with almost all elements.

Due to this high level of reactivity, the halogens are almost never found in pure form; rather, they have to be extracted. Extraction of halogens is doubly problematic, because they are dangerous. Exposure to large quantities can be harmful or fatal, and for this reason halogens have been used as poisons to deter unwanted plants and insects—and, in one of the most horrifying chapters of twentieth century military history, as a weapon in World War I.

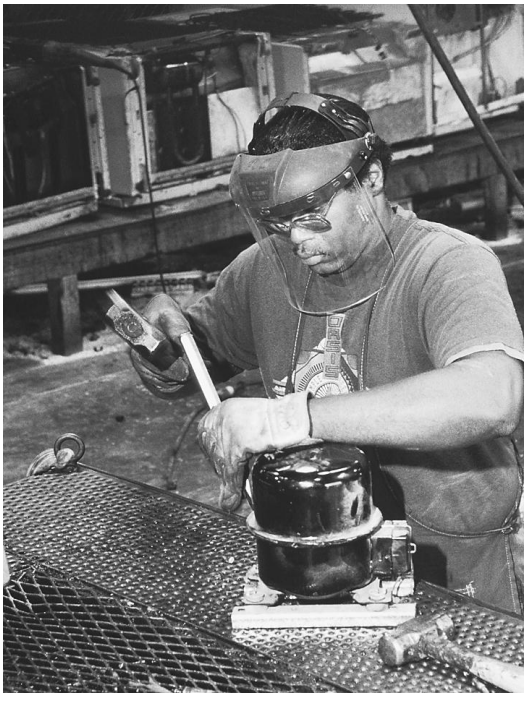
## REAL-LIFE APPLICATIONS

### CHLORINE

Chlorine is a highly poisonous gas, greenish-yellow in color, with a sharp smell that induces choking in humans. Yet, it can combine with other elements to form compounds safe for human consumption. Most notable among these compounds is salt, which has been used as a food preservative since at least 3000 B.C.

Salt, of course, occurs in nature. By contrast, the first chlorine compound made by humans was probably hydrochloric acid, created by dissolving hydrogen chloride gas in water. The first scientist to work with hydrochloric acid was Persian physician and alchemist Rhazes (ar-Razi; c. 864-c. 935), one of the most outstanding scientific minds of the medieval period. Alchemists, who in some ways were the precursors of true chemists, believed that base metals such as iron could be turned into gold. Of course this is not possible, but alchemists in about 1200 did at least succeed in dissolving gold using a mixture of hydrochloric and nitric acids known as *aqua regia*.

The first modern scientist to work with chlorine was Swedish chemist Carl W. Scheele (1742-1786), who also discovered a number of other elements and compounds, including barium, manganese, oxygen, ammonia, and glycerin. However, Scheele, who isolated it in 1774, thought that chlorine was a compound; only in 1811 did English chemist Sir Humphry Davy (1778-1829) identify it as an element. Another chemist had suggested the name "halogen" for the alleged compound, but Davy suggested that it be called chlorine instead, after the Greek word *chloros*, which indicates a sickly yellow color.



THIS WORKER IS REMOVING FREON FROM AN OLD REFRIGERATOR. CFCS LIKE FREON MAY BE RESPONSIBLE FOR THE DEPLETION OF THE OZONE LAYER. *(James A. Sugar/Corbis. Reproduced by permission.)*

**USES OF CHLORINE.** The dangers involved with chlorine have made it an effective substance to use against stains, plants, animals—and even human beings. Chlorine gas is highly irritating to the mucous membranes of the nose, mouth, and lungs, and it can be detected in air at a concentration of only 3 parts per million (ppm).

The concentrations of chlorine used against troops on both sides in World War I (beginning in 1915) was, of course, much higher. Thanks to the use of chlorine gas and other antipersonnel agents, one of the most chilling images to emerge from that conflict was of soldiers succumbing to poisonous gas. Yet just as it is harmful to humans, chlorine can be harmful to microbes, thus preserving human life. As early as 1801, it had been used in solutions as a disinfectant; in 1831, its use in hospitals made it effective as a weapon against a cholera epidemic that swept across Europe.

Another well-known use of chlorine is as a bleaching agent. Until 1785, when chlorine was

first put to use as a bleach, the only way to get stains and unwanted colors out of textiles or paper was to expose them to sunlight, not always an effective method. By contrast, chlorine, still used as a bleach today, can be highly effective—a good reason not to use regular old-fashioned bleach on anything other than white clothing. (Since the 1980s, makers of bleaches have developed all-color versions to brighten and take out stains from clothing of other colors.)

Calcium hydrocholoride (CaOCl), both a bleaching powder and a disinfectant used in swimming pools, combines both the disinfectant and bleaching properties of chlorine. This and the others discussed here are just some of many, many compounds formed with the highly reactive element chlorine. Particularly notable—and controversial—are compounds involving chlorine and carbon.

**CHLORINE AND ORGANIC COMPOUNDS.** Chlorine bonds well with organic substances, or those containing carbon. In a number of instances, chlorine becomes part of an organic polymer such as PVC (polyvinyl chloride), used for making synthetic pipe. Chlorine polymers are also applied in making synthetic rubber, or neoprene. Due to its resistance to heat, oxidation, and oils, neoprene is used in a number of automobile parts.

The bonding of chlorine with substances containing carbon has become increasingly controversial because of concerns over health and the environment, and in some cases chlorine-carbon compounds have been outlawed. Such was the fate of DDT, a pesticide soluble in fats and oils rather than in water. When it was discovered that DDT was carcinogenic, or cancer-causing, in humans and animals, its use in the United States was outlawed.

Other, less well-known, chlorine-related insecticides have likewise been banned due to their potential for harm to human life and the environment. Among these are chlorine-containing materials once used for dry cleaning. Also notable is the role of chlorine in chlorofluorocarbons (CFCs), which have been used in refrigerants such as Freon, and in propellants for aerosol sprays. CFCs tend to evaporate easily, and concerns over their effect on Earth's atmosphere have led to the phasing out of their use.

## FLUORINE

Fluorine has the distinction of being the most reactive of all the elements, with the highest electronegativity value on the periodic table. Because of this, it proved extremely difficult to isolate. Davy first identified it as an element, but was poisoned while trying unsuccessfully to decompose hydrogen fluoride. Two other chemists were also later poisoned in similar attempts, and one of them died as a result.

French chemist Edmond Fremy (1814-1894) very nearly succeeded in isolating fluorine, and though he failed to do so, he inspired his student Henri Moissan (1852-1907) to continue the project. One of the problems involved in isolating this highly reactive element was the fact that it tends to "attack" any container in which it is placed: most metals, for instance, will burst into flames in the presence of fluorine. Like the others before him, Moissan set about to isolate fluorine from hydrogen fluoride by means of electrolysis—the use of an electric current to cause a chemical reaction—but in doing so, he used a platinum-iridium alloy that resisted attacks by fluorine. In 1906, he received the Nobel Prize for his work, and his technique is still used today in modified form.

**PROPERTIES AND USES OF FLUORINE.** A pale green gas of low density, fluorine can combine with all elements except some of the noble gases. Even water will burn in the presence of this highly reactive substance. Fluorine is also highly toxic, and can cause severe burns on contact, yet it also exists in harmless compounds, primarily in the mineral known as fluorspar, or calcium fluoride. The latter gives off a fluorescent light (fluorescence is the term for a type of light not accompanied by heat), and fluorine was named for the mineral that is one of its principal "hosts".

Beginning in the 1600s, hydrofluoric acid was used for etching glass, and is still used for that purpose today in the manufacture of products such as light bulbs. The oil industry uses it as a catalyst—a substance that speeds along a chemical reaction—to increase the octane number in gasoline. Fluorine is also used in a polymer commonly known as Teflon, which provides a nonstick surface for frying pans and other cooking-related products.

Just as chlorine saw service in World War I, fluorine was enlisted in World War II to create a

weapon far more terrifying than poison gas: the atomic bomb. Scientists working on the Manhattan Project, the United States' effort to develop the bombs dropped on Japan in 1945, needed large quantities of the uranium-235 isotope. This they obtained in large part by diffusion of the compound uranium hexafluoride, which consists of molecules containing one uranium atom and six fluorine anions.

**FLUORIDATION OF WATER.** Long before World War II, health officials in the United States noticed that communities having high concentration of fluoride in their drinking water tended to suffer a much lower incidence of tooth decay. In some areas the concentration of fluoride in the water supply was high enough that it stained people's teeth; still, at the turn of the century—an era when dental hygiene as we know it today was still in its infancy—the prevention of tooth decay was an attractive prospect. Perhaps, officials surmised, it would be possible to introduce smaller concentrations of fluoride into community drinking water, with a resulting improvement in overall dental health.

After World War II, a number of municipalities around the United States undertook the fluoridation of their water supplies, using concentrations as low as 1 ppm. Within a few years, fluoridation became a hotly debated topic, with proponents pointing to the potential health benefits and opponents arguing from the standpoint of issues not directly involved in science. It was an invasion of personal liberty, they said, for governments to force citizens to drink water which had been supplemented with a foreign substance.

During the 1950s, in fact, fluoridation became associated in some circles with Communism—just another manifestation of a government trying to control its citizens. In later years, ironically, antifluoridation efforts became associated with groups on the political left rather than the right. By then, the argument no longer revolved around the issue of government power; instead the concern was for the health risks involved in introducing a substance lethal in large doses.

Fluoride had meanwhile gained application in toothpastes. Colgate took the lead, introducing "stannous fluoride" in 1955. Three years later, the company launched a memorable advertising campaign with commercials in which a little girl showed her mother a "report card" from the dentist and announced "Look, Ma! No cavities!" Within a few years, virtually all brands of toothpaste used fluoride; however, the use of fluoride in drinking water remained controversial.

As late as 1993, in fact, the issue of fluoridation remained heated enough to spawn a study by the U.S. National Research Council. The council found some improvement in dental health, but not as large as had been claimed by early proponents of fluoridation. Furthermore, this improvement could be explained by reference to a number of other factors, including fluoride in toothpastes and a generally heightened awareness of dental health among the U.S. populace.

**CHLOROFLUOROCARBONS.** Another controversial application of fluorine is its use, along with chlorine and carbon, in chlorofluorocarbons. As noted above, CFCs have been used in refrigerants and propellants; another application is as a blowing agent for polyurethane foam. This continued for several decades, but in the 1980s, environmentalists became concerned over depletion of the ozone layer high in Earth's atmosphere.

Unlike ordinary oxygen ($O_2$), ozone or $O_3$ is capable of absorbing ultraviolet radiation from the Sun, which would otherwise be harmful to human life. It is believed that CFCs catalyze the conversion of ozone to oxygen, and that this may explain the "ozone hole," which is particularly noticeable over the Antarctic in September and October.

As a result, a number of countries signed an agreement in 1996 to eliminate the manufacture of halocarbons, or substances containing halogens and carbon. Manufacturers in countries that signed this agreement, known as the Montreal Protocol, have developed CFC substitutes, most notably hydrochlorofluorocarbons (HCFCs), CFC-like compounds also containing hydrogen atoms.

The ozone-layer question is far from settled, however. Critics argue that in fact the depletion of the ozone layer over Antarctica is a natural occurrence, which may explain why it only occurs at certain times of year. This may also explain why it happens primarily in Antarctica, far from any place where humans have been using CFCs. (Ozone depletion is far less significant in the Arctic, which is much closer to the population centers of the industrialized world.)

In any case, natural sources, such as volcano eruptions, continue to add halogen compounds to the atmosphere.

## Bromine

Bromine is a foul-smelling reddish-brown liquid whose name is derived from a Greek word meaning "stink." With a boiling point much lower than that of water—137.84°F (58.8°C)—it readily transforms into a gas. Like other halogens, its vapors are highly irritating to the eyes and throat. It is found primarily in deposits of brine, a solution of salt and water. Among the most significant brine deposits are in Israel's Dead Sea, as well as in Arkansas and Michigan.

Credit for the isolation of bromine is usually given to French chemist Antoine-Jérôme Balard (1802-1876), though in fact German chemist Carl Löwig (1803-1890) actually isolated it first, in 1825. However, Balard, who published his results a year later, provided a much more detailed explanation of bromine's properties.

The first use of bromine actually predated both men by several millennia. To make their famous purple dyes, the Phoenicians used murex mollusks, which contained bromine. (Like the names of the halogens, the word "Phoenicians" is derived from Greek—in this case, a word meaning "red" or "purple," which referred to their dyes.) Today bromine is also used in dyes, and other modern uses include applications in pesticides, disinfectants, medicines, and flame retardants.

At one time, a compound containing bromine was widely used by the petroleum industry as an additive for gasoline containing lead. Ethylene dibromide reacts with the lead released by gasoline to form lead bromide ($PbBr_2$), referred to as a "scavenger," because it tends to clean the emissions of lead-containing gasoline. However, leaded gasoline was phased out during the late 1970s and early 1980s; as a result, demand for ethylene dibromide dropped considerably.

**HALOGEN LAMPS.** The name "halogen" is probably familiar to most people because of the term "halogen lamp." Used for automobile headlights, spotlights, and floodlights, the halogen lamp is much more effective than ordinary incandescent light. Incandescent "heat-producing" light was first developed in the 1870s and improved during the early part of the twentieth century with the replacement of carbon by tungsten as the principal material in the filament, the area that is heated.

Tungsten proved much more durable than carbon when heated, but it has a number of problems when combined with the gases in an incandescent bulb. As the light bulb continues to burn for a period of time, the tungsten filament begins to thin and will eventually break. At the same time, tungsten begins to accumulate on the surface of the bulb, dimming its light. However, by adding bromine and other halogens to the bulb's gas filling—thus making a halogen lamp—these problems are alleviated.

As tungsten evaporates from the filament, it combines with the halogen to form a gaseous compound that circulates within the bulb. Instead of depositing on the surface of the bulb, the compound remains a gas until it comes into contact with the filament and breaks down. It is then redeposited on the filament, and the halogen gas is free to combine with newly evaporated tungsten. Though a halogen bulb does eventually break down, it lasts much longer than an ordinary incandescent bulb and burns with a much brighter light. Also, because of the decreased tungsten deposits on the surface, it does not begin to dim as it nears the end of its life.

## Iodine

First isolated in 1811 from ashes of seaweed, iodine has a name derived from the Greek word meaning "violet-colored"—a reference to the fact it forms dark purple crystals. During the 1800s, iodine was obtained commercially from mines in Chile, but during the twentieth century wells of brine in Japan, Oklahoma, and Michigan have proven a better source.

Among the best-known properties of iodine is its importance in the human diet. The thyroid gland produces a growth-regulating hormone that contains iodine, and lack of iodine can cause a goiter, a swelling around the neck. Table salt does not naturally contain iodine; however, sodium chloride sold in stores usually contains about 0.01% sodium iodide, added by the manufacturer.

Iodine was once used in the development of photography: during the early days of photographic technology, the daguerreotype process used silver plates sensitized with iodine vapors.

## KEY TERMS

**ANION:** The negative ion that results when an atom gains one or more electrons. An anion (pronounced "AN-ie-un") of an element is never called, for instance, the chlorine anion. Rather, an anion involving a single element is named by adding the suffix -ide to the name of the original element—in this case, "chloride." Other rules apply for more complex anions.

**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 of elements in order of atomic number.

**CHEMICAL SYMBOL:** A one-or two-letter abbreviation for the name of an element.

**DIATOMIC:** A term describing an element that exists as molecules composed of two atoms. All of the halogens are diatomic.

**ELECTROLYSIS:** The use of an electrical current to cause a chemical reaction.

**HALF-LIFE:** The length of time it takes a substance to diminish to one-half its initial amount.

**HALOGENS:** Group 7 of the periodic table of elements, including fluorine, chlorine, bromine, iodine, and astatine. The halogens are diatomic, and tend to form salts; hence their name, which comes from two Greek terms meaning "salt-forming."

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

**IONIC BONDING:** A form of chemical bonding that results from attractions between ions with opposite electrical charges.

**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. Isotopes may be either stable or unstable—that is, radioactive.

**PERIODIC TABLE OF ELEMENTS:** A chart that shows the elements arranged in order of atomic number. Vertical columns within the periodic table indicate groups or "families" of elements with similar chemical characteristics.

**POLYMER:** A large molecule containing many small units that hook together.

**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. "Decay" in this sense does not mean "rot"; instead, radioactive isotopes continue to emit particles, changing into isotopes of other elements, until they become stable.

**SALT:** A compound formed by the reaction of an acid with a base. Salts are usually formed by the joining of a metal and a nonmetal.

**VALENCE ELECTRONS:** Electrons that occupy the highest energy levels in an atom, and are involved in chemical bonding. The halogens all have seven valence electrons.

Iodine compounds are used today in chemical analysis and in synthesis of organic compounds.

## ASTATINE

Just as fluorine has the distinction of being the most reactive, astatine is the rarest of all the elements. Long after its existence was predicted, chemists still had no luck finding it in nature, and it was only created in 1940 by bombarding bismuth with alpha particles (positively charged helium nuclei). The newly isolated element was given a Greek name meaning "unstable."

Indeed, none of astatine's 20 known isotopes is stable, and the longest-lived has a half-life of only 8.3 hours. This has only added to the difficulties involved in learning about this strange element, and therefore it is difficult to say what applications, if any, astatine may have. The most promising area involves the use of astatine to treat a condition known as hyperthyroidism, related to an overly active thyroid gland.

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# NOBLE GASES

## CONCEPT

Along the extreme right-hand column of the periodic table of elements is a group known as the noble gases: helium, neon, argon, krypton, xenon, and radon. Also known as the rare gases, they once were called inert gases, because scientists believed them incapable of reacting with other elements. Rare though they are, these gases are a part of everyday life, as evidenced by the helium in balloons, the neon in signs—and the harmful radon in some American homes.

## HOW IT WORKS

### Defining the Noble Gases

The periodic table of elements is ordered by the number of protons in the nucleus of an atom for a given element (the atomic number), yet the chart is also arranged in such a way that elements with similar characteristics are grouped together. Such is the case with Group 8, which is sometimes called Group 18, a collection of non-metals known as the noble gases. The six noble gases are helium (He), neon (Ne), argon (Ar), krypton (Kr), xenon (Xe), and radon (Rn). Their atomic numbers are, respectively, 2, 10, 18, 36, 54, and 86.

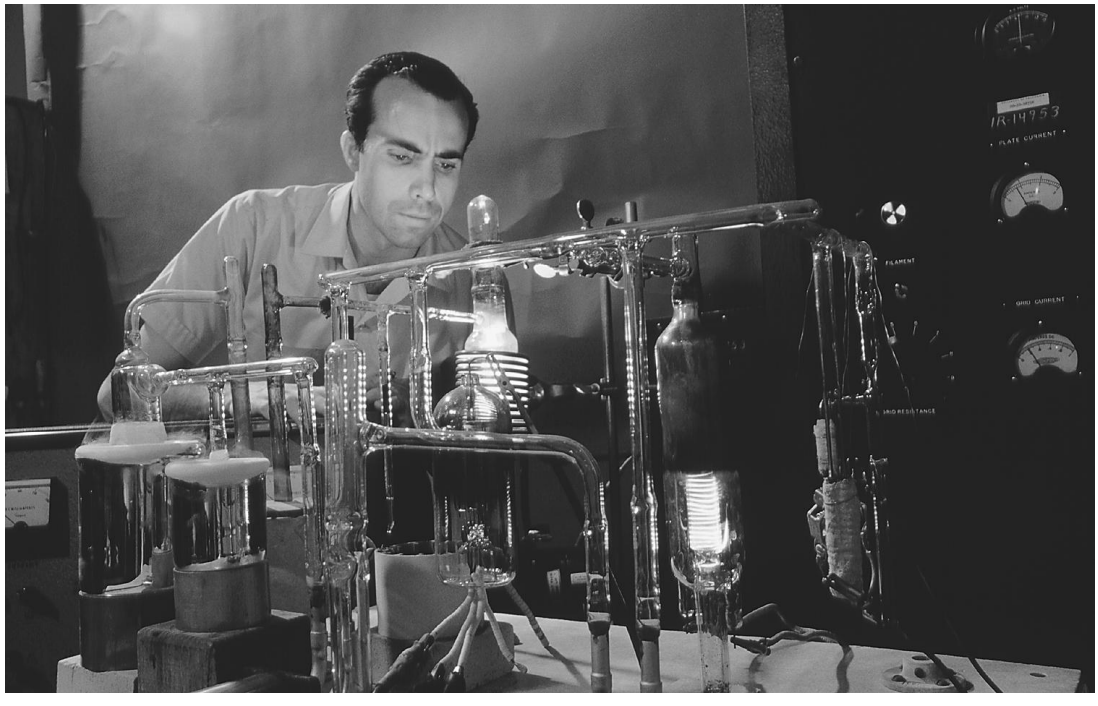
Several characteristics, aside from their placement on the periodic table, define the noble gases. Obviously, all are gases, meaning that they only form liquids or solids at extremely low temperatures—temperatures that, on Earth at least, are usually only achieved in a laboratory. They are colorless, odorless, and tasteless, as well as monatomic—meaning that they exist as individual atoms, rather than in molecules. (By contrast, atoms of oxygen—another gas, though not among this group—usually combine to form a molecule, $O_2$.)

### Low Reactivity

There is a reason why noble gas atoms tend not to combine: one of the defining characteristics of the noble gas "family" is their lack of chemical reactivity. Rather than reacting to, or bonding with, other elements, the noble gases tend to remain apart—hence the name "noble," implying someone or something that is set apart from the crowd, as it were. Due to their apparent lack of reactivity, the noble gases—also known as the rare gases—were once known as the inert gases.

Indeed, helium, neon, and argon have not been found to combine with other elements to form compounds. However, in 1962 English chemist Neil Bartlett (1932-) succeeded in preparing a compound of xenon with platinum and fluorine ($XePtF_6$), thus overturning the idea that the noble gases were entirely "inert." Since that time, numerous compounds of xenon with other elements, most notably oxygen and fluorine, have been developed. Fluorine has also been used to form simple compounds with krypton and radon.

Nonetheless, low reactivity—instead of no reactivity, as had formerly been thought—characterizes the rare gases. One of the factors governing the reactivity of an element is its electron configuration, and the electrons of the noble gases are arranged in such a way as to discourage bonding with other elements.




A scientist using the potassium-argon dating process to determine the age of materials. *(Dean Conger/Corbis. Reproduced by permission.)*

## Real-Life Applications

### Isolation of the Noble Gases

**Helium.** Helium is an unusual element in many respects—not least because it is the only element to have first been identified in the Solar System before it was discovered on Earth. This is significant, because the elements on Earth are the same as those found in space: thus, it is more than just an attempt at sounding poetic when scientists say that humans, as well as the world around them, are made from "the stuff of stars."

In 1868, a French astronomer named Pierre Janssen (1824-1907) was in India to observe a total solar eclipse. To aid him in his observations, he used a spectroscope, an instrument for analyzing the spectrum of light emitted by an object. What Janssen's spectroscope showed was surprising: a yellow line in the spectrum, never seen before, which seemed to indicate the presence of a previously undiscovered element. Janssen called it "helium" after the Greek god Helios, or Apollo, whom the ancients associated with the Sun.

Janssen shared his findings with English astronomer Sir Joseph Lockyer (1836-1920), who had a worldwide reputation for his work in analyzing light waves. Lockyer, too, believed that what Janssen had seen was a new element, and a few months later, he observed the same unusual spectral lines. At that time, the spectroscope was still a new invention, and many members of the worldwide scientific community doubted its usefulness, and therefore, in spite of Lockyer's reputation, they questioned the existence of this "new" element. Yet during their lifetimes, Janssen and Lockyer were proven correct.

**Neon, Argon, Krypton, and Xenon.** They had to wait a quarter century, however. In 1893, English chemist Sir William Ramsay (1852-1916) became intrigued by the presence of a mysterious gas bubble left over when nitrogen from the atmosphere was combined with oxygen. This was a phenomenon that had also been noted by English physicist Henry Cavendish (1731-1810) more than a century before, but Cavendish could offer no explanation. Ramsay, on the other hand, had the benefit of observations made by English physicist John William Strutt, Lord Rayleigh (1842-1919).

Up to that time, scientists believed that air consisted only of oxygen, carbon dioxide, and water vapor. However, Rayleigh had noticed that when nitrogen was extracted from air after a

process of removing those other components, it had a slightly higher density than nitrogen prepared from a chemical reaction. In light of his own observations, Ramsay concluded that whereas nitrogen obtained from chemical reactions was pure, the nitrogen extracted from air contained trace amounts of an unknown gas.

Ramsay was wrong in only one respect: hidden with the nitrogen was not one gas, but five. In order to isolate these gases, Ramsay and Rayleigh subjected air to a combination of high pressure and low temperature, allowing the various gases to boil off at different temperatures. One of the gases was helium—the first confirmation that the element existed on Earth—but the other four gases were previously unknown. The Greek roots of the names given to the four gases reflected scientists' wonder at discovering these hard-to-find elements: *neos* (new), *argos* (inactive), *kryptos* (hidden), and *xenon* (stranger).

**RADON.** Inspired by the studies of Polish-French physicist and chemist Marie Curie (1867-1934) regarding the element radium and the phenomenon of radioactivity (she discovered the element, and coined the latter term), German physicist Friedrich Dorn (1848-1916) became fascinated with radium. Studying the element, he discovered that it emitted a radioactive gas, which he dubbed "radium emanation." Eventually, however, he realized that what was being produced was a new element. This was the first clear proof that one element could become another through the process of radioactive decay.

Ramsay, who along with Rayleigh had received the Nobel Prize in 1904 for his work on the noble gases, was able to map the new element's spectral lines and determine its density and atomic mass. A few years later, in 1918, another scientist named C. Schmidt gave it the name "radon." Due to its behavior and the configuration of its electrons, chemists classified radon among what they continued to call the "inert gases" for another half-century—until Bartlett's preparation of xenon compounds in 1962.

## Presence of the Rare Gases on Earth

**IN THE ATMOSPHERE.** Though the rare gases are found in minerals and meteorites on Earth, their greatest presence is in the planet's atmosphere. It is believed that they were released into the air long ago as a by-product of decay on the part of radioactive materials in the Earth's crust. Within the atmosphere, argon is the most "abundant"—in comparative terms, given the fact that the "rare gases" are, by definition, rare.




LAS VEGAS HAS NUMEROUS EXAMPLES OF SIGNS ILLUMINATED BY NEON. *(Dave Bartruff/Corbis. Reproduced by permission.)*

Nitrogen makes up about 78% of Earth's atmosphere and oxygen 21%, meaning that these two elements constitute fully 99% of the air above the Earth. Argon ranks a distant third, with 0.93%. The remaining 0.07% is made up on water vapor, carbon dioxide, ozone ($O_3$), and traces of the noble gases. These are present in such small quantities that the figures for them are not typically presented as percentages, but rather in terms of parts per million (ppm). The concentrations of neon, helium, krypton, and xenon in the atmosphere are 18, 5, 1, and 0.09 ppm respectively.

**IN THE SOIL.** Radon in the atmosphere is virtually negligible, which is a fortunate thing, in light of its radioactive qualities. Few Americans, in fact, even knew of its existence until 1988, when the United States Environmental Protection Agency (EPA) released a report estimating that some ten million American homes had potentially harmful radon levels. This



A researcher works with liquid helium as part of an experiment on cosmic background radiation. Close to absolute zero, helium transforms into a highly unusual liquid that has no measurable resistance to flow. *(Roger Ressmeyer/Corbis. Reproduced by permission.)*

set off a scare, and during the late 1980s and 1990s, sales of home radon detectors boomed. Meanwhile, the federal government increased concerns with additional reports, advising people to seal their basements and ventilate their homes if radon exceeded certain levels.

A number of scientists have disputed the government's claims, yet some regions of the United States appear to be at relatively high risk due to the presence of radon in the soil. The element seems to be most plentiful in soils containing high concentrations of uranium. If radon is present in a home that has been weather-sealed to improve the efficiency of heating and cooling systems, it is indeed potentially dangerous to the residents.

Chinese scientists in the 1960s made an interesting discovery regarding radon and its application to seismography, or the area of the earth sciences devoted to studying and predicting earthquakes. Radon levels in groundwater, the Chinese reports showed, rise considerably just before an earthquake. Since then, the Chinese have monitored radon concentrations in water, and used this data to predict earthquakes.

**EXTRACTING RARE GASES.** Radon, in fact, is not the only rare gas that can be obtained as the result of radioactive decay: in 1903, Ramsay and British chemist Frederick Soddy (1877-1956) showed that the breakdown of either uranium or radium results in the production of helium atoms (beta particles). A few years later, English physicist Ernest Rutherford (1871-1937) demonstrated that radiation carrying a positive electrical charge (alpha rays) was actually a stream of helium atoms stripped of an electron.

Many of the noble gases are extracted by liquefying air—that is, by reducing it to temperatures at which it assumes the properties of a liquid rather than a gas. By controlling temperatures in the liquefied air, it is possible to reach the boiling point for a particular noble gas and thereby extract it, much as was done when these gases were first isolated in the 1890s.

**THE UNIQUE SITUATION OF HELIUM.** Helium is remarkable, in that it only liquefies at a temperature of -457.6°F (-272°C), just above absolute zero. Absolute zero is the temperature at which the motion of atoms or molecules comes to a virtual stop, but the motion of helium atoms never completely ceases. In order to liquefy it, in fact, even at those low

temperatures, it must be subjected to pressures many times that exerted by Earth's atmosphere.

Given these facts, it is difficult to extract helium from air. More often, it is obtained from natural gas wells, where it is present in relatively large concentrations—between 1% and 7% of the natural gas. The majority of the Earth's helium supply belongs to the United States, where the greatest abundance of helium-supplying wells are in Texas, Oklahoma, and Kansas. During World War II, the United States took advantage of this supply of relatively inexpensive helium to provide buoyancy for a fleet of airships used for reconnaissance.

There is one place with an abundant supply of helium, but there are no plans for a mining expedition any time soon. That place is the Sun, where the nuclear fusion of hydrogen atoms creates helium. Indeed, helium seems to be the most plentiful element of all, after hydrogen, constituting 23% of the total mass of the universe. Why, then, is it so difficult to obtain on Earth? Most likely because it is so light in comparison to air; it simply floats off into space.

## Applications for the Noble Gases

**RADON, ARGON, KRYPTON, AND XENON.** Though radon is known primarily for the hazards it poses to human life and well-being, it has useful applications. As noted above, its presence in groundwater appears to provide a possible means of predicting earthquakes. In addition, it is used for detecting leaks, measuring flow rates, and inspecting metal welds.

One interesting use of argon and, in particular, the stable isotope argon-40, is in dating techniques used by geologists, paleontologists, and other scientists studying the distant past. When volcanic rocks are subjected to extremely high temperatures, they release argon, and as the rocks cool, 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. The latter has a half-life of 1.3 billion years, meaning that it takes 1.3 billion years for half the potassium-40 originally present to be converted to argon-40. Using argon-40, paleontologists have been able to estimate the age of volcanic layers above and below fossil and artifact remains in east Africa.

Krypton has a number of specialized applications—for instance, it is mixed with argon and used in the manufacture of windows with a high level of thermal efficiency. Used in lasers, it is often mixed with a halogen such as fluorine. In addition, it is also sometimes used in halogen sealed-beam headlights. Many fans of *Superman*, no doubt, were disappointed at some point in their lives to discover that there is no such thing as "kryptonite," the fictional element that caused the Man of Steel to lose his legendary strength. Yet krypton—the real thing—has applications that are literally out of this world. In the development of fuel for space exploration, krypton is in competition with its sister element, xenon. Xenon offers better performance, but costs about ten times more to produce; thus krypton has become more attractive as a fuel for space flight.

In addition to its potential as a space fuel, xenon is used in arc lamps for motion-picture film projection, in high-pressure ultraviolet radiation lamps, and in specialized flashbulbs used by photographers. One particular isotope of xenon is utilized for tracing the movement of sands along a coastline. Xenon is also applied in high-energy physics for detecting nuclear radiation in bubble chambers. Furthermore, neuroscientists are experimenting with the use of xenon in diagnostic procedures to clarify x-ray images of the human brain.

**NEON.** Neon, of course, is best-known for its application in neon signs, which produce an eye-catching glow when lit up at night. French chemist Georges Claude (1870-1960), intrigued by Ramsay's discovery of neon, conducted experiments that led to the development of the neon light in 1910. That first neon light was simply a glass tube filled with neon gas, which glowed a bright red when charged with electricity.

Claude eventually discovered that mixing other gases with neon produced different colors of light. He also experimented with variations in the shapes of glass tubes to create letters and pictures. By the 1920s, neon light had come into vogue, and it is still popular today. Modern neon lamps are typically made of plastic rather than glass, and the range of colors is much greater than in Claude's day: not only the gas filling, but the coating inside the tube, is varied, resulting in a variety of colors from across the spectrum.

Though the neon sign is its best-known application, neon is used for many other things. Neon glow lamps are often used to indicate on/off settings on electronic instrument panels, and lightweight neon lamps are found on machines ranging from computers to voltage regulators. In fact, the first practical color television, produced in 1928, used a neon tube to produce the red color in the receiver. Green came from mercury, but the blue light in that early color TV came from another noble gas, helium.

**HELIUM.** Helium, of course, is widely known for its use in balloons—both for large airships and for the balloons that have provided joy and fun to many a small child. Though helium is much more expensive than hydrogen as a means of providing buoyancy to airships, hydrogen is extremely flammable, and after the infamous explosion of the airship *Hindenburg* in 1937, helium became the preferred medium for airships. As noted earlier, the United States military made extensive use of helium-filled airships during the World War II.

The use of helium for buoyancy is one of the most prominent applications of this noble gas, but far from the only one. In fact, not only have people used helium to go up in balloons, but divers use helium for going down beneath the surface of the ocean. In that situation, of course, helium is not used for providing buoyancy, but as a means of protecting against the diving-related condition known as "the bends," which occurs when nitrogen in the blood bubbles as the diver rises to the surface. Helium is mixed with oxygen in diver's air tanks because it does not dissolve in the blood as easily as nitrogen.

Among the most fascinating applications of helium relate to its extraordinarily low freezing point. Helium has played a significant role in the low-temperature science known as cryogenics, and has found application in research concerning superconductivity: the use of very low temperatures to develop materials that conduct electrical power with vastly greater efficiency than ordinary conductors. Close to absolute zero, helium transforms into a highly unusual liquid unlike any known substance, in that it has no measurable resistance to flow. This means that it could carry an electrical current hundreds of times more efficiently than a copper wire.

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# CARBON

## CONCEPT

The phrase "carbon-based life forms," often used in science-fiction books and movies by aliens to describe the creatures of Earth, is something of a cliché. It is also a redundancy when applied to creatures on Earth, the only planet known to support life: all living things contain carbon. Carbon is also in plenty of things that were once living, which makes it useful for dating the remains of past settlements on Earth. Of even greater usefulness is petroleum, a substance containing carbon-based forms that died long ago, became fossilized, and ultimately changed chemically into fuels. Then again, not all materials containing carbon were once living creatures; yet because carbon is a common denominator to all living things on Earth, the branch of study known as organic chemistry is devoted to the study of compounds containing carbon. Among the most important organic compounds are the many carboxylic acids that are vital to life, but carbon is also present in numerous important inorganic compounds—most notably carbon dioxide and carbon monoxide.

## HOW IT WORKS

### The Basics of Carbon

Carbon's name comes from the Latin word *carbo,* or charcoal—which, indeed, is almost pure carbon. Its chemical symbol is C, and it has an atomic number of 6, meaning that there are six protons in its nucleus. Its two stable isotopes are $^{12}C$, which constitutes 98.9% of all carbon found in nature, and $^{13}C$, which accounts for the other 1.1%.

The mass of the $^{12}C$ atom is the basis for the atomic mass unit (amu), by which mass figures for all other elements are measured: the amu is defined as exactly 1/12 the mass of a single $^{12}C$ atom. The difference in mass between $^{12}C$ and $^{13}C$, which is heavier because of its extra neutron, account for the fact that the atomic mass of carbon is 12.01 amu: were it not for the small quantities of $^{13}C$ present in a sample of carbon, the mass would be exactly 12.00 amu.

**WHERE CARBON IS FOUND.** Carbon makes up only a small portion of the known elemental mass in Earth's crust, oceans, and atmosphere—just 0.08%, or 1/1250 of the whole—yet 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. Thus if a person weighs 100 lb (45.3 kg), she is carrying around 18 lb (8.2 kg) of carbon—the same material from which diamonds are made!

Present in the inorganic rocks of the ground and in the living creatures above it, carbon is everywhere. Combined with other elements, it forms carbonates, most notably calcium carbonate ($CaCO_3$), which appears in the form of limestone, marble, and chalk. In combination with hydrogen, it creates hydrocarbons, present in deposits of fossil fuels: natural gas, petroleum, and coal. In the environment, carbon—in the form of carbon dioxide ($CO_2$)—is taken in by plants, which undergo the process of photosynthesis and release oxygen to animals. Animals breathe in oxygen and release carbon dioxide to the atmosphere.

### Carbon and Bonding

Located in Group 4 of the periodic table of elements (Group 14 in the IUPAC system), carbon has a valence electron configuration of $2s^2 2p^2$;

likewise, all the members of Group 4—sometimes known as the "carbon family"—have configurations of $ns^2np^2$, where $n$ is the number of the period or row that the element occupies on the table.

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. Silicon, found in virtually all types of rocks except the calcium carbonates (mentioned above), is to the inorganic world what carbon is to the organic. Yet silicon atoms are about one and a half times as large as those of carbon; thus not even silicon can compete with carbon's ability to form a seemingly limitless array of molecules in various shapes and sizes, and having various chemical properties.

**BASICS OF CHEMICAL BONDING.** Carbon is further distinguished by its high value of electronegativity, the relative ability of an atom to attract valence electrons. Electronegativity increases with an increase in group number, and decreases with an increase in period number. In other words, the elements with the highest electronegativity values lie in the upper right-hand corner of the periodic table.

Actually, the previous statement requires one significant qualification: the extreme right-hand side of the periodic table is occupied by elements with negligible electronegativity values. These are the noble gases, which have eight valence electrons each. Eight, as it turns out, is the "magic number" for chemical bonding: most elements follow what is known as the octet rule, meaning that when one element bonds to another, the two atoms have eight valence electrons.

If the two atoms have an electric charge and thus are ions, they form strong ionic bonds. Ionic bonding occurs when a metal bonds with a nonmetal. The other principal type of bond is a covalent bond, in which two uncharged atoms share eight valence electrons. If the electronegativity values of the two elements involved are equal, they share the electrons equally; but if one element has a higher electronegativity value, the electrons will be more drawn to that element.

**ELECTRONEGATIVITY OF CARBON.** To return to electronegativity and the periodic table, let us ignore the noble gases, which are the chemical equivalent of snobs. (Hence the term "noble," meaning that they are set apart.) To the left of the noble gases are the halogens, a wildly gregarious bunch—none more so than the element that occupies the top of the column, fluorine. With an electronegativity value of 4.0, fluorine is the most reactive of all elements, and the only one capable of bonding even to a few of the noble gases.

So why is fluorine—capable of forming multitudinous bonds—not as chemically significant as carbon? There are a number of answers, but a simple one is this: because fluorine is too strong, and tends to "overwhelm" other elements, precluding the possibility of forming long chains, it is less chemically significant than carbon. Carbon, on the other hand, has an electronegativity value of 2.5, which places it well behind fluorine. Yet it is still at sixth place (in a tie with iodine and sulfur) on the periodic table, behind only fluorine; oxygen (3.5); nitrogen and chlorine (3.0); and bromine (2.8). In addition, with four valence electrons, carbon is ideally suited to find other elements (or other carbon atoms) for forming covalent bonds according to the octet rule.

**MULTIPLE 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 is capable of forming not only a single bond, but also a double bond, or even a triple bond, with other elements.

Suppose a carbon atom bonds to two oxygen atoms to form carbon dioxide. Let us imagine these three atoms side by side, with the oxygen in the middle. (This, in fact, is how these bonds are depicted in the Couper and Lewis systems of chemical symbolism, discussed in the Chemical Bonding essay.) We know that the carbon has four valence electrons, that the oxygens have six, and that the goal is for each atom to have eight valence electrons—some of which it will share covalently.

Two of the valence electrons from the carbon bond with two valence electrons each from the oxygen atoms on either side. This means that the carbon is doubly bonded to each of the oxygen atoms. Therefore, the two oxygens each have four other unbonded valence electrons, which might bond to another atom. It is theoretically possible, also, for the carbon to form a triple

bond with one of the oxygens by sharing three of its valence electrons. It would then have one electron free to share with the other oxygen.

## REAL-LIFE APPLICATIONS

### ORGANIC CHEMISTRY

We have stated that carbon forms tetravalent bonds, and makes multiple bonds with a single atom. In addition, we have mentioned the fact that carbon forms long chains of atoms and varieties of shapes. But how does it do these things, and why? These are good questions, but not ones we will attempt to answer here. In fact, an entire branch of chemistry is devoted to answering these theoretical questions, as well as to determining solutions to a host of other, more practical problems.

Organic chemistry is the study of carbon, its compounds, and their properties. (There are carbon-containing compounds that are not considered organic, however. Among these are oxides such as carbon dioxide and monoxide; as well as carbonates, most notably calcium carbonate.) 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, German chemist Friedrich Wöhler (1800-1882) cracked the code that distinguished the living from the nonliving, and the organic from the inorganic.

Wöhler took a sample of ammonium cyanate ($NH_4OCN$), and by heating it, converted it into urea ($H_2N\text{-}CO\text{-}NH_2$), a waste product in the urine of mammals. In other words, he had turned an inorganic material into a organic one, and he did so, as he observed, "without benefit of a kidney, a bladder, or a dog." It was almost as though he had created life. In fact, what Wöhler had glimpsed—and what other scientists who followed came to understand, was this: what separates the organic from the inorganic is the manner in which the carbon chains are arranged.

Ammonium cyanate and urea have exactly the same numbers and proportions of atoms, yet they are different compounds. They are thus isomers: substances which have the same formula, but are different chemically. In urea, the carbon forms an organic chain, and in ammonium cyanate, it does not. Thus, to reduce the specifics of organic chemistry even further, it can be said that this area of the field constitutes the study of carbon chains, and ways to rearrange them in order to create new substances.

Rubber, vitamins, cloth, and paper are all organically based compounds we encounter in our daily lives. In each case, the material comes from something that once was living, but what truly makes these substance organic in nature is the common denominator of carbon, as well as the specific arrangements of the atoms. We have organic chemistry to thank for any number of things: aspirins and all manner of other drugs; preservatives that keep food from spoiling; perfumes and toiletries; dyes and flavorings, and so on.

### ALLOTROPES OF CARBON

**GRAPHITE.** Carbon has several allotropes—different versions of the same element, distinguished by molecular structure. The first of these is graphite, a soft material with an unusual crystalline structure. 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. A piece of graphite is thus like a big, thick stack of carbon paper: on the one hand, the stack is heavy, but 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 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. This is not surprising, considering that pencil "lead" is, in fact, a mixture of graphite, clay, and wax. In ancient times, people did indeed use lead—the heaviest member of Group 4, the "carbon family"—for writing, because it left gray marks on a surface. Lead, of course, is poisonous, and is not used today in pencils or in most applications that would involve prolonged exposure of humans to the element. Nonetheless, people still use the word "lead" in reference to pencils, much as they still

refer to a galvanized steel roof with a zinc coating as a "tin roof."

In graphite the atoms of each "sheet" are tightly bonded in a hexagonal, or six-sided, pattern, but the attractions between the sheets are not very strong. This makes it highly useful as a lubricant for locks, where oil would tend to be messy. A good conductor of electricity, graphite is also utilized for making high-temperature electrolysis cells. In addition, the fact that graphite resists temperatures of up to about 6,332°F (3,500°C) makes it useful in electric motors and generators.

**DIAMOND.** The second allotrope of carbon is also crystalline in structure. This is diamond, most familiar in the form of jewelry, but in fact widely applied for a number of other purposes. According to the Moh scale, which measures the hardness of minerals, diamond is a 10—in other words, the hardest type of material. It is used for making drills that bore through solid rock; likewise, small diamonds are used in dentists' drills for boring through the ultra-hard enamel on teeth.

Neither diamonds nor graphite are, in the strictest sense of the term, 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 forever. Whereas graphite is in the form of sheets, a diamond is basically a huge "molecule" composed of carbon atoms strung together by covalent bonds. The size of this "molecule" corresponds to the size of the diamond: a diamond of 1 carat, for instance, contains about $10^{22}$ (10,000,000,000,000,000,000,000 or 10 billion billion) carbon atoms.

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.

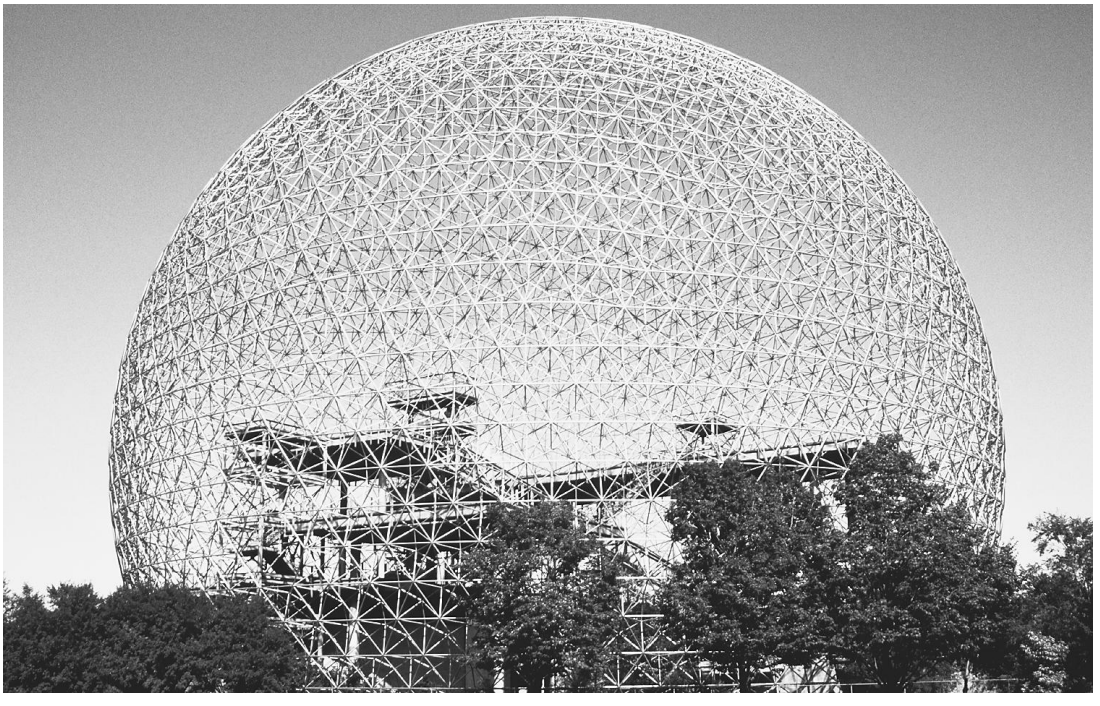
The cutting of fine diamonds for jewelry is an art, exemplified in the alluring qualities of such famous gems as the jewels in the British Crown or the infamous Hope Diamond in Washington, D.C.'s Smithsonian Institution. Such diamonds—as well as the diamonds on an engagement ring—are cut to refract or bend light rays, and to disperse the colors of visible light.

**BUCKMINSTERFULLERENE.** Until 1985, carbon was believed to exist in only two crystalline forms, graphite and diamond. In that year, however, chemists at Rice University in Houston, Texas, and at the University of Sussex in England, discovered a third variety of carbon—and later jointly received a Nobel Prize for their work. This "new" carbon molecule composed of 60 bonded atoms in the shape of what is called a "hollow truncated icosahedron." In plain language, this is rather like a soccer ball, with interlocking pentagons and hexagons. However, because the surface of each geometric shape is flat, the "ball" itself is not a perfect sphere. Rather, it describes the shape of a geodesic dome, a design created by American engineer and philosopher R. Buckminster Fuller (1895-1983).

There are other varieties of buckminsterfullerene molecules, known as fullerenes. However, the 60-atom shape, designated as $^{60}C$, is the most common of all fullerenes, the result of condensing carbon slowly at high temperatures. Fullerenes potentially have a number of applications, particularly because they exhibit a whole range of electrical properties: some are insulators, while some are conductors, semiconductors, and even superconductors. Due to the high cost of producing fullerenes artificially, however, the ways in which they are applied remain rather limited.

**AMORPHOUS CARBON.** There is a fourth way in which carbon appears, distinguished from the other three in that it is amorphous, as opposed to crystalline, in structure. An example of amorphous carbon is carbon black, obtained from smoky flames and used in ink, or for blacking rubber tires.

Though it retains some of the microscopic structures of the plant cells in the wood from which it is made, charcoal—wood or other plant material that has been heated without enough air present to make it burn—is mostly amorphous carbon. One form of charcoal is activated charcoal, in which steam is used to remove the sticky products of wood decomposition. What remains are porous grains of pure carbon with enormous microscopic surface areas. These are used in water purifiers and gas masks.



A geodesic dome in Montreal, Quebec, Canada. Such domes are named after their designer, R. Buckminster Fuller, and eventually provided the name for the carbon molecules known as buckminsterfullerenes. *(Lee Snider/Corbis. Reproduced by permission.)*

Coal and coke are particularly significant varieties of amorphous carbon. Formed by the decay of fossils, coal was one of the first "fossil fuels" (for example, petroleum) used to provide heat and power for industrial societies. Indeed, when the words "industrial revolution" are mentioned, many people picture tall black smokestacks belching smoke from coal fires. Fortunately— from an environmental standpoint—coal is not nearly so widely used today, and when it is (as for instance in electric power plants), the methods for burning it are much more efficient than those applied in the nineteenth century.

Actually, much of what those smokestacks of yesteryear burned was coke, a refined version of coal that contains almost pure carbon. Produced by heating soft coal in the absence of air, coke has a much greater heat value than coal, and is still widely used as a reducing agent in the production of steel and other alloys.

## Carbon Dioxide

Carbon forms many millions of compounds, some families of which will be discussed below. Two others, formed by the bonding of carbon atoms with oxygen atoms, are of particular significance. In carbon dioxide, a single carbon joins with two oxygens to produce a gas essential to plant life. In carbon monoxide (CO), a single oxygen joins the carbon, creating a toxic—but nonetheless important—compound.

The first gas to be distinguished from ordinary air, carbon dioxide is an essential component in the natural balance between plant and animal life. Animals, including humans, produce carbon dioxide by breathing, and humans further produce it by burning wood and other fuels. Plants use carbon dioxide when they store energy in the form of food, and they release oxygen to be used by animals.

**DISCOVERY.** Flemish chemist and physicist Johannes van Helmont (1579-1644) discovered in 1630 that air was not, as had been thought up to that time, a single element: it contained a second substance, produced in the burning of wood, which he called "gas sylvestre." Thus he is recognized as the first scientist to note the existence of carbon dioxide.

More than a century later, in 1756, Scottish chemist Joseph Black (1728-1799) showed that carbon dioxide—which he called "fixed air"—combines with other chemicals to form compounds. This and other determinations Black made concerning carbon dioxide led to enor-




Soft drinks are made possible by the use of carbonated water. *(Sergio Dorantes/Corbis. Reproduced by permission.)*

mous progress in the discovery of gases by various chemists of the late eighteenth century.

By that time, chemists had begun to arrive at a greater degree of understanding with regard to the 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. Carbon dioxide and its role in the connection between animal and plant life provided a much more sophisticated explanation as to the ways plants "breathe."

**uses.** Around the same time that Black made his observations on carbon dioxide, English chemist Joseph Priestley (1733-1804) became the first scientist to put the chemical to use. Dissolving it in water, he created carbonated water, which today is used in making soft drinks. Not only does the gas add bubbles to drinks, it also acts as a preservative.

Though the natural uses of carbon dioxide are by far the most important, the compound has numerous industrial and commercial applications. Used in fire extinguishers, carbon dioxide is ideal for controlling electrical and oil fires, which cannot be put out with water. Heavier than air, carbon dioxide blankets the flames and smothers them.

In the solid form of dry ice, carbon dioxide is used for chilling perishable food during transport. It is also one of the only compounds that experiences sublimation, or the instantaneous transformation of a solid to a gas without passing through an intermediate liquid state, at conditions of ordinary pressure and temperature. Dry ice has often been used in movies to generate "mists" or "smoke" in a particular scene.

## Carbon Monoxide

During the late eighteenth century, Priestley discovered a carbon-oxygen compound different from carbon dioxide: carbon monoxide. Scientists had actually known of this toxic gas, released in the incomplete combustion of wood, from the Middle Ages onward, but Priestley was the first to identify it scientifically.

Industry uses carbon monoxide in a number of ways. By blowing air across very hot coke, the result is producer gas, which, along with water gas (made by passing hot steam over coal) is an important fuel. Producer gas constitutes a 6:1:18 mixture of carbon monoxide, carbon dioxide, and nitrogen, while water gas is 40% carbon monoxide, 50% hydrogen, and 10% carbon dioxide and other gases.

## KEY TERMS

**ALLOTROPES:** Different versions of the same element, distinguished by molecular structure.

**AMORPHOUS:** Having no definite structure.

**CARBOHYDRATES:** Naturally occurring compounds of carbon, hydrogen, and oxygen. These are primarily produced by green plants through the process of photosynthesis.

**CELLULAR RESPIRATION:** The process whereby nutrients from plants are broken down in an animal's body to create carbon dioxide.

**COVALENT BONDING:** A type of chemical bonding in which two atoms share valence electrons.

**CRYSTALLINE:** A term describing a type of solid in which the constituent parts have a simple and definite geometric arrangement that is repeated in all directions.

**DOUBLE BOND:** A form of bonding in which two atoms share two pairs of valence electrons. Carbon is also capable of single bonds and triple bonds.

**ELECTRONEGATIVITY:** The relative ability of an atom to attract valence electrons.

**ION:** An atom or group of atoms that has lost or gained one or more electrons, and thus has a net electric charge.

**IONIC BONDING:** A form of chemical bonding that results from attractions between ions with opposite electric charges.

**ISOMERS:** Substances which have the same chemical formula, but which are different chemically due to differences in the arrangement of atoms.

**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. Isotopes may be either stable or unstable. The latter type, known as radioisotopes, are radioactive.

**OCTET RULE:** A term describing the distribution of valence electrons that takes place in chemical bonding for most elements, which usually end up with eight valence electrons.

**ORGANIC CHEMISTRY:** The study of carbon, its compounds, and their properties. (Many carbon-containing oxides and carbonates are not considered organic, however.)

**PHOTOSYNTHESIS:** The biological conversion of light energy (that is, electromagnetic energy) to chemical energy in plants.

**RADIOACTIVITY:** A term describing a phenomenon whereby certain isotopes known as radioisotopes are subject to a form of decay brought about by the emission of high-energy particles. "Decay" does not mean that the isotope "rots"; rather, it decays to form another isotope until eventually (though this may take a long time) it becomes stable.

**SINGLE BOND:** A form of bonding in which two atoms share one pair of valence electrons. Carbon is also capable of double bonds and triple bonds.

**TETRAVALENT:** Capable of bonding to four other elements.

## KEY TERMS continued

**triple bond:** A form of bonding in which two atoms share three pairs of valence electrons. Carbon is also capable of single bonds and double bonds.

**valence electrons:** Electrons that occupy the highest principal energy level in an atom. These are the electrons involved in chemical bonding.

Not only are producer and water gas used for fuel, they are also applied as reducing agents. Thus, when carbon monoxide is passed over hot iron oxides, the oxides are reduced to metallic iron, while the carbon monoxide is oxidized to form carbon dioxide. Carbon monoxide is also used in reactions with metals such as nickel, iron, and cobalt to form some types of carbonyls.

Carbon monoxide—produced by burning petroleum in automobiles, as well as by the combustion of wood, coal, and other carbon-containing fuels—is extremely hazardous to human health. It bonds with iron in hemoglobin, the substance in red blood cells that transports oxygen throughout the body, and in effect 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.

### Carbon and the Environment

Carbon is released into the atmosphere by one of three means: cellular respiration; the burning of fossil fuels; and the eruption of volcanoes. When plants take in carbon dioxide from the atmosphere, they combine this 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.

In the process of undergoing photosynthesis, plants produce carbohydrates, which are various compounds of carbon, hydrogen, and oxygen essential to life. The other two fundamental components of a diet are fats and proteins, both 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. Cellular respiration is the process whereby these nutrients are broken down to create carbon dioxide.

Photosynthesis and cellular respiration are thus linked in what is known as the carbon cycle. Cellular respiration also releases carbon into the atmosphere through the action of decomposers—bacteria and fungi that feed on the remains of plants and animals. The decomposers extract the energy in the chemical bonds of the decomposing matter, thus releasing more carbon dioxide into the atmosphere.

When creatures die and are buried in such a way that they cannot be reached by decomposers—for instance, at the bottom of the ocean, or beneath layers of rock—the carbon in their bodies is eventually converted to fossil fuels, including petroleum, natural gas, and coal. The burning of fossil fuels releases carbon (both monoxide and dioxide) into the atmosphere.

Because the rate of such burning has increased dramatically since the late nineteenth century, this has raised fears that carbon dioxide in the atmosphere may create a greenhouse effect, leading to global warming. On the other hand, volcanoes release tons of carbon into the atmosphere regardless of whether humans burn fossil fuels or not.

### Radiocarbon Dating

Radiocarbon dating is used to date the age of charcoal, wood, and other biological materials. 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.

Carbon-14 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. Therefore a scientist can use the ratios of carbon-12, carbon-14, and nitrogen-14 to guess the age of an organic sample. The problem with radiocarbon dating, however, is that there is a good likelihood the sample can become contaminated by additional carbon from the soil. Furthermore, it cannot be said with certainty that the ratio of carbon-12 to carbon-14 in the atmosphere has been constant throughout time.

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# HYDROGEN

## CONCEPT

First element on the periodic table, hydrogen is truly in a class by itself. It does not belong to any family of elements, and though it is a nonmetal, it appears on the left side of the periodic table with the metals. The other elements with it in Group 1 form the alkali metal family, but obviously, hydrogen does not belong with them. Indeed, if there is any element similar to hydrogen in simplicity and abundance, it is the only other one on the first row, or period, of the periodic table: helium. Together, these two elements make up 99.9% of all known matter in the entire universe, because hydrogen atoms in stars fuse to create helium. Yet whereas helium is a noble gas, and therefore chemically unreactive, hydrogen bonds with all sorts of other elements. In one such variety of bond, with carbon, hydrogen forms the backbone for a vast collection of organic molecules, known as hydrocarbons and their derivatives. Bonded with oxygen, hydrogen forms the single most important compound on Earth, and the most important complex substance other than air: water. Yet when it bonds with sulfur, it creates toxic hydrogen sulfide; and on its own, hydrogen is extremely flammable. The only element whose isotopes have names, hydrogen has long been considered as a potential source of power and transportation: once upon a time for airships, later as a component in nuclear reactions—and, perhaps in the future, as a source of abundant clean energy.

## HOW IT WORKS

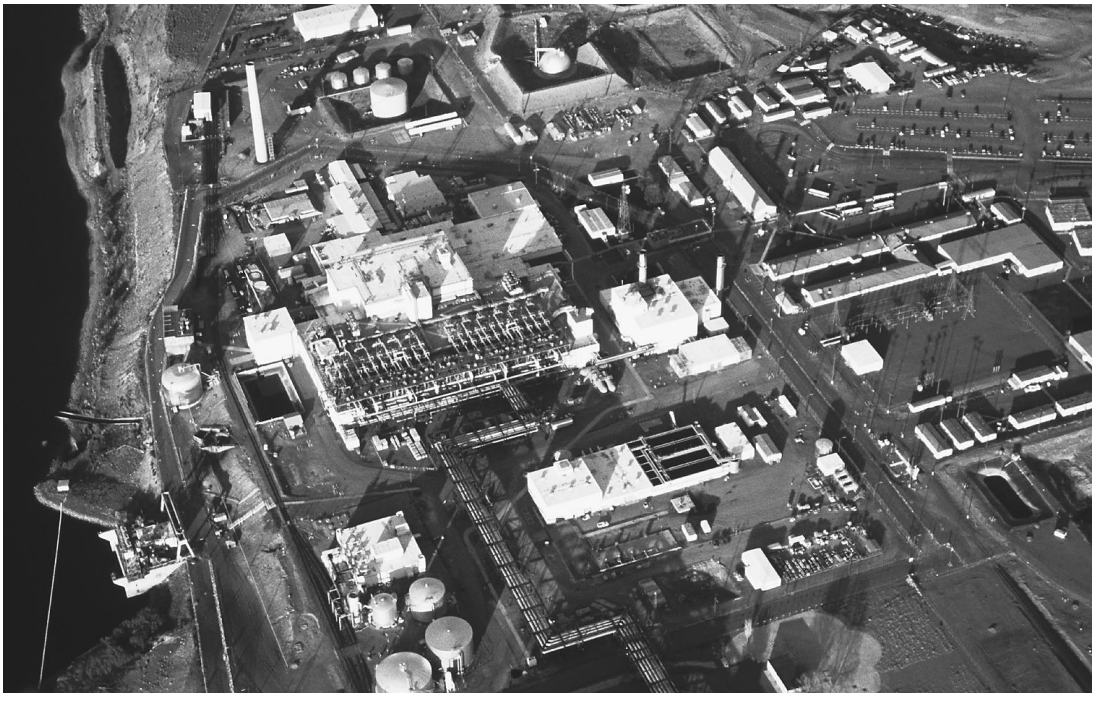
### The Essentials

The atomic number of hydrogen is 1, meaning that it has a single proton in its nucleus. With its single electron, hydrogen is the simplest element of all. Because it is such a basic elemental building block, figures for the mass of other elements were once based on hydrogen, but the standard today is set by $^{12}C$ or carbon-12, the most common isotope of carbon.

Hydrogen has two stable isotopes—forms of the element that differ in mass. The first of these, protium, is simply hydrogen in its most common form, with no neutrons in its nucleus. Protium (the name is only used to distinguish it from the other isotopes) accounts for 99.985% of all the hydrogen that appears in nature. The second stable isotope, deuterium, has one neutron, and makes up 0.015% of all hydrogen atoms. Tritium, hydrogen's one radioactive isotope, will be discussed below.

The fact that hydrogen's isotopes have separate names, whereas all other isotopes are designated merely by element name and mass number (for example, "carbon-12") says something about the prominence of hydrogen as an element. Not only is its atomic number 1, but in many ways, it is like the number 1 itself—the essential piece from which all others are ultimately constructed. Indeed, nuclear fusion of hydrogen in the stars is the ultimate source for the 90-odd elements that occur in nature.

The mass of this number-one element is not, however, 1: it is 1.008 amu, reflecting the small quantities of deuterium, or "heavy hydrogen," present in a typical sample. A gas at ordinary temperatures, hydrogen turns to a liquid at -423.2°F (-252.9°C), and to a solid at –434.°F (–259.3°C). These figures are its boiling point and melting point respectively; only the figures for helium are lower. As noted earlier, these two elements make up all but 0.01% of the known



AMONG THE USES OF TRITIUM IS IN FUEL FOR HYDROGEN BOMBS. SHOWN HERE IS THE HANFORD PLANT IN THE STATE OF WASHINGTON, WHERE SUCH FUEL IS PRODUCED. *(Roger Ressmeyer/Corbis. Reproduced by permission.)*

elemental mass of the universe, and are the principal materials from which stars are formed.

Normally hydrogen is diatomic, meaning that its molecules are formed by two atoms. At the interior of a star, however, where the temperature is many millions of degrees, $H_2$ molecules are separated into atoms, and these atoms become ionized. In other words, the electron separates from the proton, resulting in an ion with a positive charge, along with a free electron. The positive ions experience fusion—that is, their nuclei bond, releasing enormous amounts of energy as they form new elements.

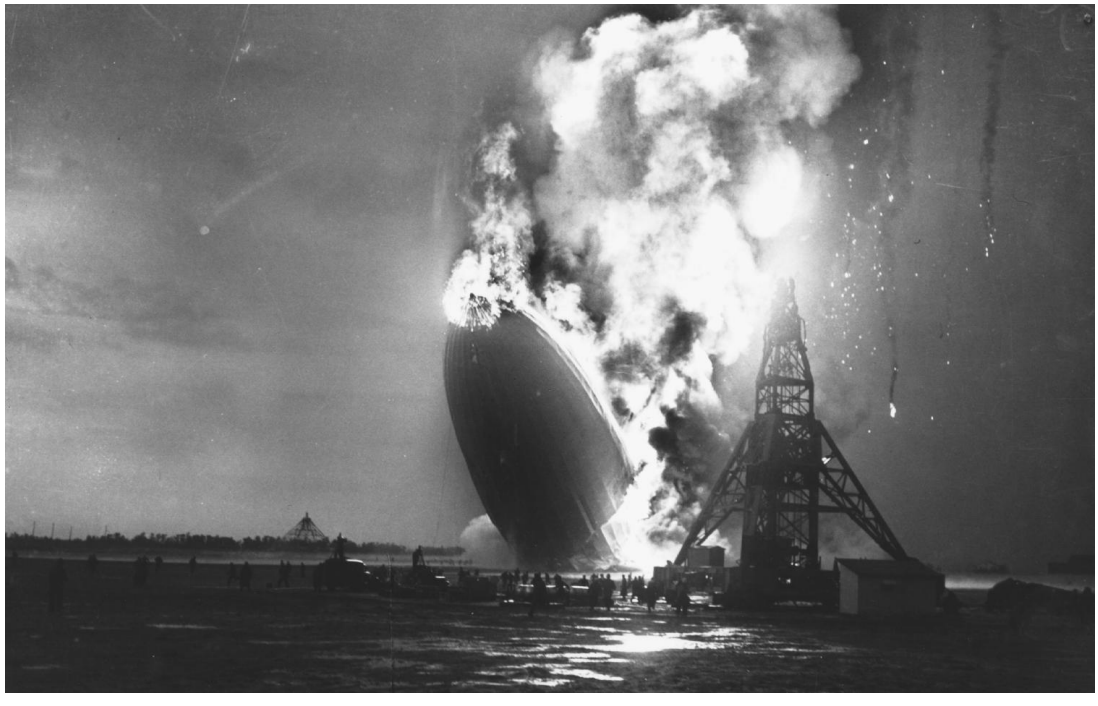
Because the principal isotopic form of helium has two protons in the nucleus, it is natural that helium is the element usually formed; yet it is nonetheless true—amazing as it may seem—that all the elements found on Earth were once formed in stars. On Earth, however, hydrogen ranks ninth in its percentage of the planet's known elemental mass: just 0.87%. In the human body, on the other hand, it is third, after oxygen and carbon, making up 10% of human elemental body mass.

## HYDROGEN AND BONDING

Having just one electron, hydrogen can bond to other atoms in one of two ways. The first option is to combine its electron with one from the atom of a nonmetallic element to make a covalent bond, in which the two electrons are shared. Hydrogen is unusual in this regard, because most atoms conform to the octet rule, ending up with eight valence electrons. The bonding behavior of hydrogen follows the duet rule, resulting in just two electrons for bonding.

Examples of this first type of bond include water ($H_2O$), hydrogen sulfide ($H_2S$), and ammonia ($NH_3$), as well as the many organic compounds formed on a hydrogen-carbon backbone. But hydrogen can form a second type of bond, in which it gains an extra electron to become the negative ion H-, or hydride. It is then able to combine with a metallic positive ion to form an ionic bond. Ionic hydrides are convenient sources of hydrogen gas: for instance, calcium hydride, or $CaH_2$, is sold commercially, and provides a very convenient means of hydrogen generation. The hydrogen gas produced by the reaction of calcium hydride with water can be used to inflate life rafts.

The presence of hydrogen in certain types of molecules can also be a factor in intermolecular bonding. Intermolecular bonding is the attraction between molecules, as opposed to the bond-



The use of hydrogen in airships effectively ended with the crash of the Hindenburg in 1937. *(UPI/Corbis-Bettmann. Reproduced by permission.)*

ing within molecules, which is usually what chemists mean when they talk about "bonding."

### Hydrogen's Early History

Because it bonds so readily with other elements, hydrogen almost never appears in pure elemental form on Earth. Yet by the late fifteenth century, chemists recognized that by adding a metal to an acid, hydrogen was produced. Only in 1766, however, did English chemist and physicist Henry Cavendish (1731-1810) recognize hydrogen as a substance distinct from all other "airs," as gases then were called.

Seventeen years later, in 1783, French chemist Antoine Lavoisier (1743-1794) named the substance after two Greek words: *hydro* (water) and *genes* (born or formed). It was another two decades before English chemist John Dalton (1766-1844) formed his atomic theory of matter, and despite the great strides he made for science, Dalton remained convinced that hydrogen and oxygen in water formed "water atoms." Around the same time, however, Italian physicist Amedeo Avogadro (1776-1856) clarified the distinction between atoms and molecules, though this theory would not be generally accepted until the 1850s.

Contemporary to Dalton and Avogadro was Swedish chemist Jons Berzelius (1779-1848), who developed a system of comparing the mass of various atoms in relation to hydrogen. This method remained in use for more than a century, until the discovery of neutrons, protons, and isotopes pointed the way toward a means of making more accurate determinations of atomic mass. In 1931, American chemist and physicist Harold Urey (1893-1981) made the first separation of an isotope: deuterium, from ordinary water.

## Real-Life Applications

### Deuterium and Tritium

Designated as $^{2}H$, deuterium is a stable isotope, whereas tritium—$^{3}H$—is unstable, or radioactive. Not only do these two have names; they even have chemical symbols (D and T, respectively), as though they were elements on the periodic table. Just as hydrogen represents the most basic proton-electron combination against which other atoms are compared, these two are respectively the most basic isotope containing a single neu-

tron, and the most basic radioisotope, or radioactive isotope.

Deuterium is sometimes called "heavy hydrogen," and its nucleus is called a deuteron. In separating deuterium—an achievement for which he won the 1934 Nobel Prize—Urey collected a relatively large sample of liquid hydrogen: 4.2 qt (4 l). He then allowed the liquid to evaporate very slowly, predicting that the more abundant protium would evaporate more quickly than the heavier isotope. When all but 0.034 oz (1 ml) of the sample had evaporated, he submitted the remainder to a form of analysis called spectroscopy, adding a burst of energy to the atoms and then analyzing the light spectrum they emitted for evidence of differing varieties of atoms.

With an atomic mass of 2.014102 amu, deuterium is almost exactly twice as heavy as protium, which has an atomic mass of 1.007825. Its melting points and boiling points, respectively –426°F (–254°C) and –417°F (–249°C), are higher than for protium. Often, deuterium is applied as a tracer, an atom or group of atoms whose participation in a chemical, physical, or biological reaction can be easily observed.

**DEUTERIUM IN WAR AND PEACE.** In nuclear power plants, deuterium is combined with oxygen to form "heavy water" ($D_2O$), which likewise has higher boiling and melting points than ordinary water. Heavy water is often used in nuclear fission reactors to slow down the fission process, or the splitting of atoms. Deuterium is also present in nuclear fusion, both on the Sun and in laboratories.

During the period shortly after World War II, physicists developed a means of duplicating the thermonuclear fusion process. The result was the hydrogen bomb—more properly called a fusion bomb—whose detonating device was a compound of lithium and deuterium called lithium deuteride. Vastly more powerful than the "atomic" (that is, fission) bombs dropped by the United States over Japan (Nagaski and Hiroshima) in 1945, the hydrogen bomb greatly increased the threat of worldwide nuclear annihilation in the postwar years.

Yet the power that could destroy the world also has the potential to provide safe, abundant fusion energy from power plants—a dream as yet unrealized. Physicists studying nuclear fusion are attempting several approaches, including a process involving the fusion of two deuterons. This fusion would result in a triton, the nucleus of tritium, along with a single proton. Theoretically, the triton and deuteron would then be fused to create a helium nucleus, resulting in the production of vast amounts of energy.

**TRITIUM.** Whereas deuterium has a single neutron, tritium—as its mass number of 3 indicates—has two. And just as deuterium has approximately twice the mass of protium, tritium has about three times the mass, or 3.016 amu. Its melting and boiling points are higher still than those of deuterium: thus tritium heavy water ($T_2O$) melts at 40°F (4.5°C), as compared with 32°F (0°C) for $H_2O$.

Tritium has a half-life (the length of time it takes for half the radioisotopes in a sample to become stable) of 12.26 years. As it decays, its nucleus emits a low-energy beta particle, which is either an electron or a subatomic particle called a positron, resulting in the creation of the helium-3 isotope. Due to the low energy levels involved, the radioactive decay of tritium poses little danger to humans. In fact, there is always a small quantity of tritium in the atmosphere, and this quantity is constantly being replenished by cosmic rays.

Like deuterium, tritium is applied in nuclear fusion, but due to its scarcity, it is usually combined with deuterium. Sometimes it is released in small quantities into the groundwater as a means of monitoring subterranean water flow. It is also used as a tracer in biochemical processes, and as an ingredient in luminous paints.

## Hydrogen and Oxygen

**WATER.** Water, of course, is the most well-known compound involving hydrogen. Nonetheless, it is worthwhile to consider the interaction between hydrogen and oxygen, the two ingredients in water, which provides an interesting illustration of chemistry in action.

Chemically bonded as water, hydrogen and oxygen can put out any type of fire except an oil or electrical fire; as separate substances, however, hydrogen and oxygen are highly flammable. In an oxyhydrogen torch, the potentially explosive reaction between the two gases is controlled by a gradual feeding process, which produces combustion instead of the more violent explosion that sometimes occurs when hydrogen and oxygen come into contact.

**hydrogen peroxide.** Aside from water, another commonly used hydrogen-oxygen compound is hydrogen peroxide, or $H_2O_2$. A colorless liquid, hydrogen peroxide is chemically unstable (not "unstable" in the way that a radioisotope is), and decomposes slowly to form water and oxygen gas. In high concentrations, it can be used as rocket fuel.

By contrast, the hydrogen peroxide used in homes as a disinfectant and bleaching agent is only a 3% solution. The formation of oxygen gas molecules causes hydrogen peroxide to bubble, and this bubbling is quite rapid when the peroxide is placed on cuts, because the enzymes in blood act as a catalyst to speed up the reaction.

## Hydrogen Chloride

Another significant compound involving hydrogen is hydrogen chloride, or HCl—in other words, one hydrogen atom bonded to chlorine, a member of the halogens family. Dissolved in water, it produces hydrochloric acid, used in laboratories for analyses involving other acids. Normally, hydrogen chloride is produced by the reaction of salt with sulfuric acid, though it can also be created by direct bonding of hydrogen and chlorine at temperatures above 428°F (250°C).

Hydrogen chloride and hydrochloric acid have numerous applications in metallurgy, as well as in the manufacture of pharmaceuticals, dyes, and synthetic rubber. They are used, for instance, in making pharmaceutical hydrochlorides, water-soluble drugs that dissolve when ingested. Other applications include the production of fertilizers, synthetic silk, paint pigments, soap, and numerous other products.

Not all hydrochloric acid is produced by industry, or by chemists in laboratories. Active volcanoes, as well as waters from volcanic mountain sources, contain traces of the acid. So, too, does the human body, which generates it during digestion. However, too much hydrochloric acid in the digestive system can cause the formation of gastric ulcers.

## Hydrogen Sulfide

It may not be a pleasant subject, but hydrogen—in the form of hydrogen sulfide—is also present in intestinal gas. The fact that hydrogen sulfide is an extremely malodorous substance once again illustrates the strange things that happen when elements bond: neither hydrogen nor sulfur has any smell on its own, yet together they form an extremely noxious—and toxic—substance.

Pockets of hydrogen sulfide occur in nature. If a person were to breathe the vapors for very long, it could be fatal, but usually, the foul odor keeps people away. The May 2001 *National Geographic* included two stories relating to such natural hydrogen-sulfide deposits, on opposite sides of the Earth, and in both cases the presence of these toxic fumes created interesting results.

In southern Mexico is a system of caves known as Villa Luz, through which run some 20 underground springs, many of them carrying large quantities of hydrogen sulfide. The National Geographic Society's team had to enter the caves wearing gas masks, yet the area teems with strange varieties of life. Among these are fish that are red from high concentrations of hemoglobin, or red blood cells. The creatures need this extra dose of hemoglobin, necessary to move oxygen through the body, in order to survive on the scant oxygen supplies. The waters of the cave are further 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 supported by a grant from the National Geographic Society examined evidence suggesting that there indeed had been a great ancient flood in the area, much like the one depicted in the Bible. In their efforts, they had an unlikely ally: hydrogen sulfide, which had formed at the bottom of the sea, and was covered by dense layers of salt water. Because the Black Sea lacks the temperature differences that cause water to circulate from the bottom upward, the hydrogen sulfide stayed at the bottom.

Under normal circumstances, the wreck of a 1,500-year-old wooden ship would not have been preserved; but because oxygen could not reach the bottom of the Black Sea—and thus wood-boring worms could not live in the toxic environment—the ship was left undisturbed. Thanks to the presence of hydrogen sulfide, explorers were able to study the ship, the first fully intact ancient shipwreck to be discovered.

## Hydrocarbons

Together with carbon, hydrogen forms a huge array of organic materials known as hydrocar-

bons—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. Not only does carbon form itself into seemingly limitless molecular shapes, but hydrogen is a particularly good partner. Because it has the smallest atom of any element on the periodic table, it can bond to one of carbon's valence electrons without getting in the way of the others.

Hydrocarbons may either be saturated or unsaturated. A saturated hydrocarbon is one in which the carbon atom is already bonded to four other atoms, and thus cannot bond to any others. In an unsaturated hydrocarbon, however, not all the valence electrons of the carbon atom are bonded to other atoms.

Hydrogenation is a term describing any chemical reaction in which hydrogen atoms are added to carbon multiple bonds. There are many applications of hydrogenation, but one that is particularly relevant to daily life involves its use in turning unsaturated hydrocarbons into saturated ones. When treated with hydrogen gas, unsaturated fats (fats are complex substances that involve hydrocarbons bonded to other molecules) become saturated fats, which are softer and more stable, and stand up better to the heat of frying. Many foods contain hydrogenated vegetable oil; however, saturated fats have been linked with a rise in blood cholesterol levels—and with an increased risk of heart disease.

**PETROCHEMICALS AND FUNCTIONAL GROUPS.** One important variety of hydrocarbons is described under the collective heading of petrochemicals—that is, derivatives of petroleum. These include natural gas; petroleum ether, a solvent; naphtha, a solvent (for example, paint thinner); gasoline; kerosene; fuel for heating and diesel fuel; 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.

Then there are the many hydrocarbon derivatives formed by the bonding of hydrocarbons to various functional groups—broad arrays of molecule types involving other elements. Among these are alcohols—both ethanol (the alcohol in beer and other drinks) and methanol, used in adhesives, fibers, and plastics, and as a fuel. Other functional groups include aldehydes, ketones, carboxylic acids, and esters. Products of these functional groups range from aspirin to butyric acid, which is in part responsible for the smell both of rancid butter and human sweat. Hydrocarbons also form the basis for polymer plastics such as Nylon and Teflon.

## Hydrogen for Transportation and Power

We have already seen that hydrogen is a component of petroleum, and that hydrogen is used in creating nuclear power—both deadly and peaceful varieties. But hydrogen has been applied in many other ways in the transportation and power industries.

There are only three gases practical for lifting a balloon: hydrogen, helium, and hot air. Each is much less dense than ordinary air, and this gives them their buoyancy. Because hydrogen is the lightest known gas and is relatively cheap to produce, it initially seemed the ideal choice, particularly for airships, which made their debut near the end of the nineteenth century.

For a few decades in the early twentieth century, airships were widely used, first in warfare and later as the equivalent of luxury liners in the skies. One of the greatest such craft was Germany's *Hindenburg*, which used hydrogen to provide buoyancy. Then, on May 6, 1937, the *Hindenburg* caught fire while mooring at Lakehurst, New Jersey, and 36 people were killed—a tragic and dramatic event that effectively ended the use of hydrogen in airships.

Adding to the pathos of the *Hindenburg* crash was the voice of radio announcer Herb Morrison, whose audio report has become a classic of radio history. Morrison had come to Lakehurst to report on the landing of the famous airship, but ended up with the biggest—and most horrifying—story of his career. As the ship burst into flames, Morrison's voice broke, and he uttered words that have become famous: "Oh, the humanity!"

Half a century later, a hydrogen-related disaster destroyed a craft much more sophisticated than the *Hindenburg*, and this time, the medium of television provided an entire nation with a view of the ensuing horror. The event was the explosion of the space shuttle *Challenger* on January 28, 1986, and the cause was the failure of a rubber seal in the shuttle's fuel tanks. As a result,

## KEY TERMS

**COVALENT BONDING:** A type of chemical bonding in which two atoms share valence electrons.

**DIATOMIC:** A term describing an element that exists as molecules composed of two atoms.

**DUET RULE:** A term describing the distribution of valence electrons when hydrogen atoms—which end up with only two valence electrons—experience chemical bonding with other atoms. Most other elements follow the octet rule.

**ELECTROLYSIS:** The use of an electric current to cause a chemical reaction.

**FISSION:** A nuclear reaction involving the splitting of atoms.

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

**HYDROCARBON:** Any chemical compound whose molecules are made up of nothing but carbon and hydrogen atoms.

**HYDROGENATION:** A chemical reaction in which hydrogen atoms are added to carbon multiple bonds, as in a hydrocarbon.

**ION:** An atom or group of atoms that has lost or gained one or more electrons, and thus has a net electrical charge.

**IONIC BONDING:** A form of chemical bonding that results from attractions between ions with opposite electric charges. The bonding of a metal to a nonmetal such as hydrogen is ionic.

**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 either be stable or radioactive.

**NUCLEUS:** The center of an atom, a region where protons and neutrons are located, and around which electrons spin. The plural of "nucleus" is nuclei.

**OCTET RULE:** A term describing the distribution of valence electrons that takes place in chemical bonding for most elements, which end up with eight valence electrons. Hydrogen is an exception, and follows the duet rule.

**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.

**RADIOISOTOPE:** An isotope subject to the decay associated with radioactivity. A radioisotope is thus an unstable isotope.

**SATURATED:** A term describing a hydrocarbon in which each carbon is already bound to four other atoms.

**TRACER:** An atom or group of atoms whose participation in a chemical, physical, or biological reaction can be easily observed. Radioisotopes are often used as tracers.

**UNSATURATED:** A term describing a hydrocarbon, in which the carbons involved in a multiple bond are free to bond with other atoms.

**VALENCE ELECTRONS:** Electrons that occupy the highest principal energy level in an atom. These are the electrons involved in chemical bonding.

hydrogen gas flooded out of the craft and straight into the jet of flame behind the rocket. All seven astronauts aboard were killed.

**THE FUTURE OF HYDROGEN POWER.** Despite the misfortunes that have occurred as a result of hydrogen's high flammability, the element nonetheless holds out the promise of cheap, safe power. Just as it made possible the fusion, or hydrogen, bomb—which fortunately has never been dropped in wartime, but is estimated to be many hundreds of times more lethal than the fission bombs dropped on Japan—hydrogen may be the key to the harnessing of nuclear fusion, which could make possible almost unlimited power.

A number of individuals and agencies advocate another form of hydrogen power, created by the controlled burning of hydrogen in air. Not only is hydrogen an incredibly clean fuel, producing no by-products other than water vapor, it is available in vast quantities from water. In order to separate it from the oxygen atoms, electrolysis would have to be applied—and this is one of the challenges that must be addressed before hydrogen fuel can become a reality.

Electrolysis requires enormous amounts of electricity, which would have to be produced before the benefits of hydrogen fuel could be realized. Furthermore, though the burning of hydrogen could be controlled, there are the dangers associated with transporting it across country in pipelines. Nonetheless, a number of advocacy groups—some of whose Web sites are listed below—continue to promote efforts toward realizing the dream of nonpolluting, virtually limitless, fuel.

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# BONDING AND REACTIONS

CHEMICAL BONDING

COMPOUNDS

CHEMICAL REACTIONS

OXIDATION-REDUCTION REACTIONS

CHEMICAL EQUILIBRIUM

CATALYSTS

ACIDS AND BASES

ACID-BASE REACTIONS

# CHEMICAL BONDING

## CONCEPT

Almost everything a person sees or touches in daily life—the air we breathe, the food we eat, the clothes we wear, and so on—is the result of a chemical bond, or, more accurately, many chemical bonds. Though a knowledge of atoms and elements is essential to comprehend the subjects chemistry addresses, the world is generally not composed of isolated atoms; rather, atoms bond to one another to form molecules and hence chemical compounds. Not all chemical bonds are created equal: some are weak, and some very strong, a difference that depends primarily on the interactions of electrons between atoms.

## HOW IT WORKS

### Early Ideas of Bonding

The theory that all of matter is composed of atoms did not originate in modern times: the atomic model actually dates back to the fifth century B.C. in Greece. The leading exponent of atomic theory in ancient times was Democritus (c. 460-370 B.C.), who proposed that matter could not be infinitely subdivided. At its deepest substructure, Democritus maintained, the material world was made up of tiny fragments he called *atomos*, a Greek term meaning "no cut" or "indivisible"

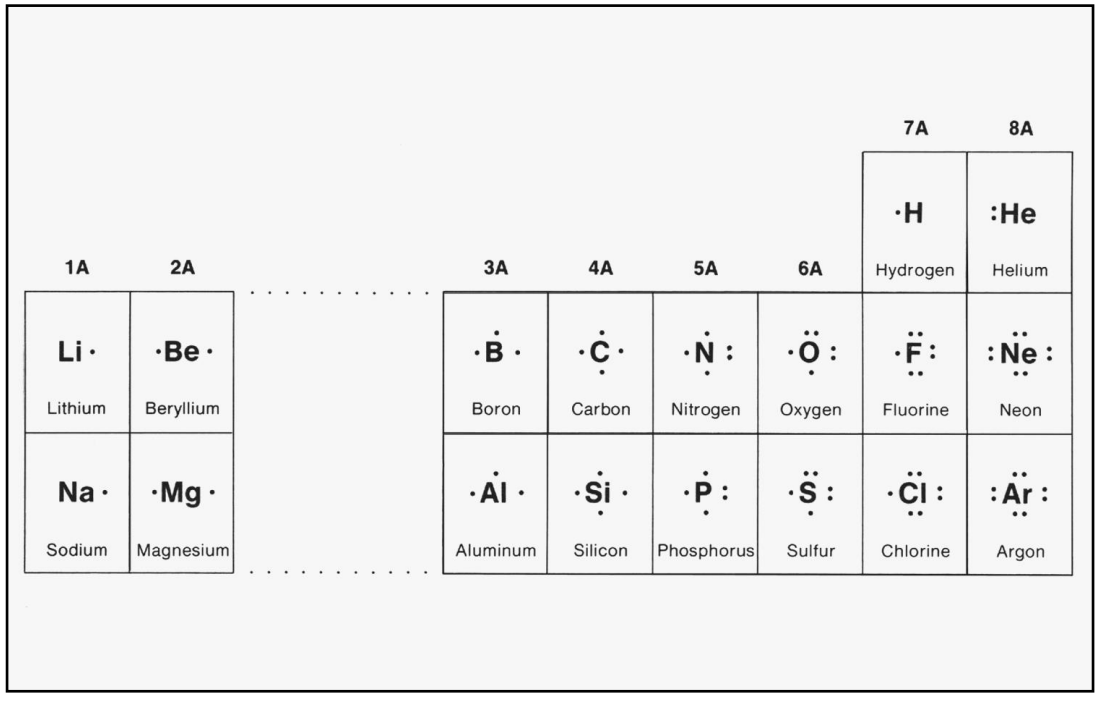
Forward-thinking though it was, Democritus's idea was not what modern scientists today would describe as a proper scientific hypothesis. His "atoms" were not purely physical units, but rather idealized philosophical constructs, and thus, he was not really approaching the subject from the perspective of a scientist. In any case, there was no way for Democritus to test his hypothesis even if he had wanted to: by their very nature, the atoms he described were far too small to observe. Even today, what scientists know about atomic behavior comes not from direct observation, but indirect means.

Hence, Democritus and the few other ancients who subscribed to atomic theory went more on instinct than by scientific methods. Yet, some of them were remarkably prescient in their description of the bonding of atoms, in view of the primitive scientific methods they had at their disposal. No other scientist came close to the accuracy of their theory for about 2,000 years.

**ASCLEPIADES AND LUCRETIUS DISCUSS BONDS.** The physician Asclepiades of Prusa (c.130-40 B.C.) drew on the ideas of the Greek philosopher Epicurus (341-270 B.C., another proponent of atomism. Asclepiades speculated on the ways in which atoms interact, and discussed "clusters of atoms," though, of course, he had no idea what force attracted the atoms to one another.

A few years after Asclepiades, the Roman philosopher and poet Lucretius (c.95-c.55 B.C. espoused views that combined atomism with the idea of the "four elements"—earth, air, fire, and water. In his great work *De rerum natura* ("On the Nature of Things"), Lucretius described atoms as tiny spheres attached to each other by fishhook-like appendages that became entangled with one another.

**LACK OF PROGRESS UNTIL 1800.** Unfortunately, the competing idea of the four elements, handed down by the great philosopher Aristotle (384-322 B.C.), prevailed over the atomic model. As the Roman Empire




Electron-dot diagrams of some elements in the periodic table. *(Robert L. Wolke. Reproduced by permission.)*

began to decline after A.D. 200, the pace of scientific inquiry slowed and—in Western Europe at least—eventually came to a virtual halt. Hence, the four elements theory, which had its own fanciful explanations as to why certain "elements" bonded with one another, held sway in Europe until the beginning of the modern era.

During the seventeenth century, a mounting array of facts from the realms of astronomy and physics collectively disproved the Aristotelian model. In the area of chemistry, English physicist and chemist Robert Boyle (1627-1691) showed that the four elements were not elements at all, because they could be broken down into simpler substances. Yet, no one really understood what constituted an element until the very beginning of the nineteenth century, and until that question was addressed, it was difficult to move on to the mystery of why certain atoms bonded with one another.

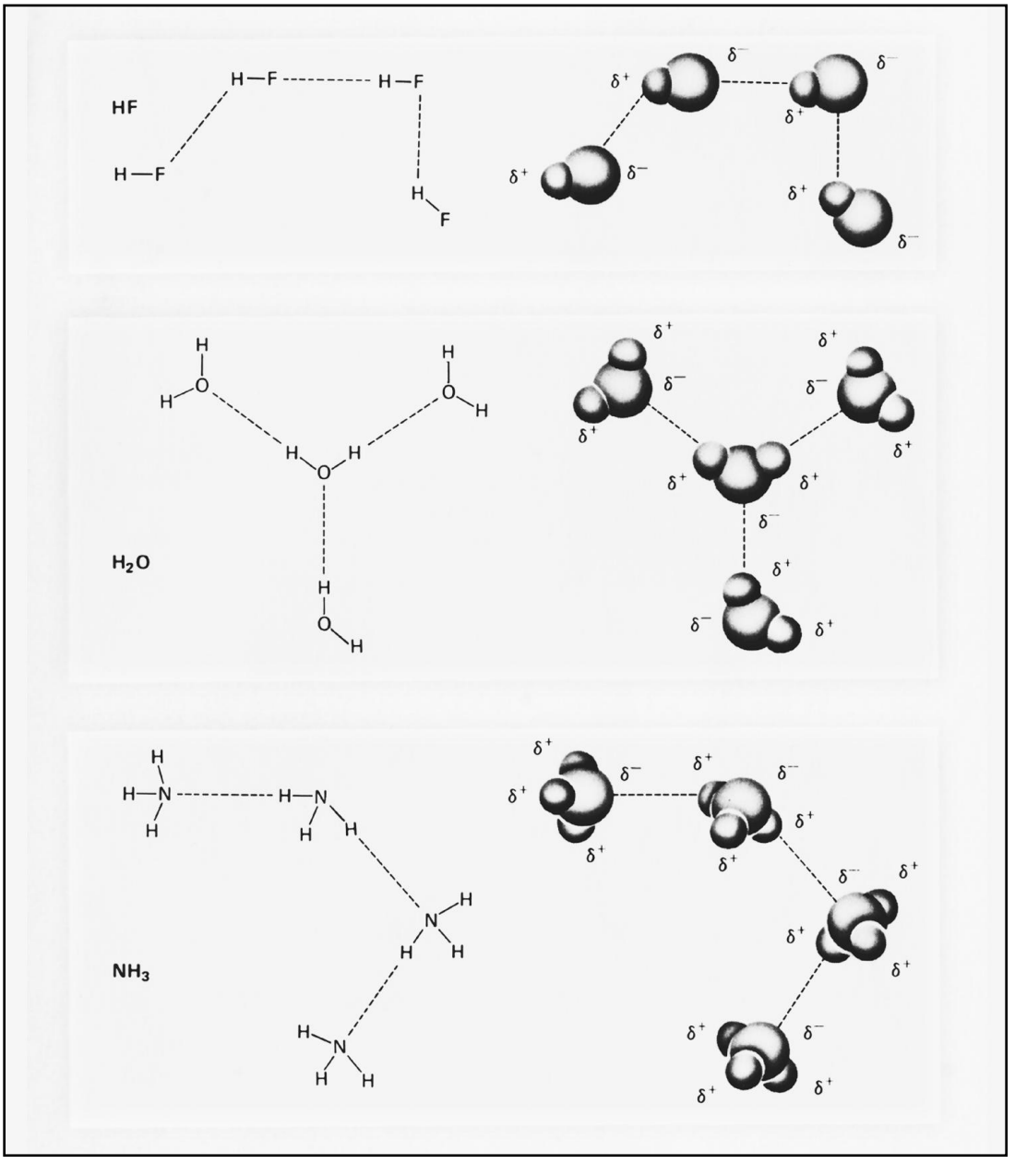
## Early Modern Advances in Bonding Theory

**Dalton's atomic theory.** The birth of atomic theory in modern times occurred in 1803, when English chemist John Dalton (1766-1844) formulated the idea that all elements are composed of tiny, indestructible particles. These he called by the name Democritus had given them nearly 23 centuries earlier: atoms. All known substances, he said, are composed of some combination of atoms, which differ from one another only in mass.

Though Dalton's theory paved the way for enormous advances in the years that followed, there were a number of flaws in it. Mass alone, for instance, is not really what differentiates one atom from another: differences in mass reflect the presence of subatomic particles—protons and neutrons—of whose existence scientists were unaware at the time.

Furthermore, the properties of atoms that cause them to bond relate to a third subatomic particle, the electron, which, though it contributes little to the mass of the atom, is all-important to the energy it possesses. As for how atoms bond to one another, Dalton had little to say: in his conception of the atomic model, atoms simply sit adjacent to one another without forming true bonds, as such.

**Avogadro and the molecule.** Though Dalton recognized that the structure of atoms in a particular element or compound is uniform, he maintained that compounds are made up of compound atoms: thus,




Hydrogen bonding in HF, $H_2O$, and $NH_3$. *(Robert L. Wolke. Reproduced by permission.)*

water is a compound of "water atoms." However, water is not an element, and therefore, there had to be some structure—still very small, but larger than the atom—in which atoms coalesced to form the basic materials of a compound.

That structure was the molecule, first described by Italian physicist Amedeo Avogadro (1776-1856). For several decades, Avogadro, who originated the idea of the mole as a means of comparing large groups of atoms or molecules, remained a more or less unsung hero. Only in 1860, four years after his death, was his idea of the molecule resurrected by Italian chemist Stanislao Cannizzaro (1826-1910). Cannizzaro's work was occasioned by disagreement among scientists regarding the determination of atomic mass; however, the establishment of the molecular model had far-reaching implications for theories of bonding.

**SYMBOLIZING ATOMIC BONDS.** In 1858, German chemist Friedrich August Kekulé (1829-1896) made the first attempt to define the concept of valency, or the property an atom of one element possesses that determines



"Pure" water from a mountain stream is actually filled with traces of the rocks over which it has flowed. In fact, water is almost impossible to find in pure form except by purifying it in a laboratory. *(David Muench/Corbis. Reproduced by permission.)*

its ability to bond with atoms of other elements. A pioneer in organic chemistry, which deals with chemical structures containing carbon, Kekulé described the carbon atom as tetravalent, meaning that it can bond to four other atoms. (The Latin prefix *tetra-* means "four.") He also speculated that carbon atoms are capable of bonding with one another in long chains.

This was one of the first attempts to examine the subject of bonding using modern scientific terminology, complete with hypotheses that could be tested by experimentation. Kekulé also recognized that in order to discuss bonds understandably, there needed to be some means of representing those bonds with symbols. He even went so far as to develop a system for showing the arrangement of bonds in space; however, his system was so elaborate that it was replaced in favor of a simpler one developed by Scottish chemist Archibald Scott Couper (1831-1892).

Couper, who also studied valency and the tetravalent carbon bond—he is usually given equal credit with Kekulé for these ideas—created an extremely straightforward schematic representation still in use by chemists today. In Couper's system, short dashed lines serve to designate chemical bonds. Hence, the bond between two hydrogen atoms and an oxygen atom in a water molecule would be represented thus: H-O-H. As the understanding of bonds progressed in modern times, this system was modified to take into account multiple bonds, discussed below.

## REAL-LIFE APPLICATIONS

### Atoms, Electrons, and Ions

Today, chemical bonding is understood as the joining of atoms through electromagnetic force. Before that understanding could be achieved, however, scientists had to unlock the secret of the electromagnetic interactions that take place within an atom.

The key to bonding is the electron, discovered in 1897 by English physicist J. J. Thomson (1856-1940). Atomic structure in general, and the properties of the electron in particular, are discussed at length elsewhere in this volume. However, because these specifics are critical to bonding, they will be presented here in the shortest possible form.

At the center of an atom is a nucleus, consisting of protons, with a positive electrical charge; and neutrons, which have no charge. These form the bulk of the atom's mass, but they have little to do with bonding. In fact, the neutron has nothing to do with it, while the proton plays only a passive role, rather like a flower being pollinated by a bee. The "bee" is the electron, and, like a bee, it buzzes to and fro, carrying a powerful "sting"—its negative electric charge, which attracts it to the positively charged proton.

**ELECTRONS AND IONS.** Though the electron weighs much, much less than a proton, it possesses enough electric charge to counterbalance the positive charge of the proton. All atoms have the same number of protons as electrons, and hence the net electric charge is zero. However, as befits their highly active role, electrons are capable of moving from one atom to another under the proper circumstances. An atom that loses or acquires electrons has an electric charge, and is called an ion.

The atom that has lost an electron or electrons becomes a positively charged ion, or cation. On the other hand, an atom that gains an electron or electrons becomes a negatively charged ion, or anion. As we shall see, ionic bonds, such as those that join sodium and chlorine atoms to form NaCl, or salt, are extremely powerful.

**ELECTRON CONFIGURATION.** Even in covalent bonding, which does not involve ions, the configurations of electrons in two atoms are highly important. The basics of electron configuration are explained in the Electrons essay, though even there, this information is presented with the statement that the student should consult a chemistry textbook for a more exhaustive explanation.

In the simplest possible terms, electron configuration refers to the distribution of electrons at various positions in an atom. However, because the behavior of electrons cannot be fully predicted, this distribution can only be expressed in terms of probability. An electron moving around the nucleus of an atom can be compared to a fly buzzing around some form of attractant (e.g., food or a female fly, if the moving fly is male) at the center of a sealed room. We can state positively that the fly is in the room, and we can predict that he will be most attracted to the center, but we can never predict his location at any given moment.

As one moves along the periodic table of elements, electron configurations become ever more complex. The reason is that with an increase in atomic number, there is an increase in the energy levels of atoms. This indicates a greater range of energies that electrons can occupy, as well as a greater range of motion. Electrons occupying the highest energy level in an atom are

called valence electrons, and these are the only ones involved in chemical bonding. By contrast, the core electrons, or the ones closest to the nucleus, play no role in the bonding of atoms.

## Ionic and Covalent Bonds

**THE GOAL OF EIGHT VALENCE ELECTRONS.** The above discussion of the atom, and the electron's place in it, refers to much that was unknown at the time Thomson discovered the electron. Protons were not discovered for several more years, and neutrons several decades after that. Nonetheless, the electron proved the key to solving the riddle of how substances bond, and not long after Thomson's discovery, German chemist Richard Abegg (1869-1910) suggested as much.

While studying noble gases, noted for their tendency not to bond, Abegg discovered that these gases always 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 has been shown to be the case in most stable chemical compounds.

**TWO DIFFERENT TYPES OF BONDS.** Perhaps, Abegg hypothesized, 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" one another.

Ionic bonds, which occur when a metal bonds with a nonmetal are extremely strong. As noted earlier, salt is an example of an ionic bond: the metal sodium loses an electron, forming a cation; meanwhile, the nonmetal chlorine gains the electron to become an anion. Their ionic bond results from the attraction of opposite charges.

Ionic bonding, however, could not explain all types of chemical bonds for the simple reason that not all compounds are ionic. A few years after Abegg's death, American chemist Gilbert Newton Lewis (1875-1946) discovered a very different type of bond, in which nonionic compounds share electrons. The result, once again, is eight valence electrons for each atom, but in this case, the nuclei of the two atoms share electrons.

In ionic bonding, two ions start out with different charges and end up forming a bond in which both have eight valence electrons. In the type of bond Lewis described, a covalent bond, two atoms start out as atoms do, with a net charge of zero. Each ends up possessing eight valence electrons, but neither atom "owns" them; rather, they share electrons.

**LEWIS STRUCTURES.** In addition to discovering the concept of covalent bonding, Lewis developed the Lewis structure, a means of showing schematically how valence electrons are arranged among the atoms in a molecule. Also known as the electron-dot system, Lewis structures represent the valence electrons as dots surrounding the chemical symbols of the atoms involved. These dots, which look rather like a colon, may be above or below, or on either side of, the chemical symbol. (The dots above or below the chemical symbol are side-by-side, like a colon turned at a 90°-angle.)

To obtain the Lewis structure representing a chemical bond, it is first necessary to know the number of valence electrons involved. One pair of electrons is always placed between elements, indicating the bond between them. Sometimes this pair of valence electrons is symbolized by a dashed line, as in the system developed by Couper. The remaining electrons are distributed according to the rules by which specific elements bond.

**MULTIPLE BONDS.** Hydrogen bonds according to what is known as the duet rule, meaning that a hydrogen atom has only two valence electrons. In most other elements—there are exceptions, but these will not be discussed here—atoms end up with eight valence electrons, and thus are said to follow the octet rule. If the bond is covalent, the total number of valence electrons will not be a multiple of eight, however, because the atoms share some electrons.

When carbon bonds to two oxygen atoms to form carbon dioxide ($CO_2$), it is represented in the Couper system as O-C-O. The Lewis structure also uses dashed lines, which stand for two valence electrons shared between atoms. In this case, then, the dashed line to the left of the carbon atom indicates a bond of two electrons with the oxygen atom to the left, and the dashed line to the right of it indicates a bond of two electrons with the oxygen atom on that side.

The non-bonding valence electrons in the oxygen atoms can be represented by sets of two dots above, below, and on the outside of each atom, for a total of six each. Combined with the two dots for the electrons that bond them to carbon, this gives each oxygen atom a total of eight valence electrons. So much for the oxygen atoms, but something is wrong with the representation of the carbon atom, which, up to this point, is shown only with four electrons surrounding it, not eight.

In fact carbon in this particular configuration forms not a single bond, but a double bond, which is represented by two dashed lines—a symbol that looks like an equals sign. By showing the double bonds joining the carbon atom to the two oxygen atoms on either side, the carbon atom has the required number of eight valence electrons. The carbon atom may also form a triple bond (represented by three dashed lines, one above the other) with an oxygen atom, in which case the oxygen atom would have only two other valence electrons.

## Electronegativity and Polar Covalent Bonds

Today, chemists understand that most bonds are neither purely ionic nor purely covalent; rather, there is a wide range of hybrids between the two extremes. Credit for this discovery belongs to American chemist Linus Pauling (1901-1994), who, in the 1930s, developed the concept of electronegativity—the relative ability of an atom to attract valence electrons.

Elements capable of bonding are assigned an electronegativity value ranging from a minimum of 0.7 for cesium to a maximum of 4.0 for fluorine. Fluorine is capable of bonding with some noble gases, which do not bond with any other elements or each other. The greater the electronegativity value, the greater the tendency of an element to draw valence electrons to itself.

If fluorine and cesium bond, then, the bond would be purely ionic, because the fluorine exerts so much more attraction for the valence electrons. But if two elements have equal electronegativity values—for instance, cobalt and silicon, both of which are rated at 1.9—the bond is purely covalent. Most bonds, as stated earlier, fall somewhere in between these two extremes.

**POLAR COVALENT BONDING.** When substances of differing electronegativity values form a covalent bond, this is described as polar covalent bonding. Sometimes these are simply called "polar bonds," but that is not as accurate: all ionic bonds, after all, are polar, due to the extreme differences in electronegativity. The term "polar covalent bond" is much more specific, describing a bond, for instance, between hydrogen (2.1) and sulfur (2.6). Because sulfur has a slightly greater electronegativity value, the valence electrons will be slightly more attracted to the sulfur atom than to the hydrogen atom.

Another example of a polar covalent bond is the one that forms between hydrogen and oxygen (3.5) to form $H_2O$ or water, which has a number of interesting properties. For instance, the polar quality of a water molecule gives it a great attraction for ions, and thus ionic substances such as salt dissolve easily in water. "Pure" water from a mountain stream is actually filled with traces of the rocks over which it has flowed. In fact, water—sometimes called the "universal solvent"—is almost impossible to find in pure form, except when it is purified in a laboratory.

By contrast, molecules of petroleum ($CH_2$) tend to be nonpolar, because carbon and hydrogen have almost identical electronegativity values—2.5 and 2.1 respectively. Thus, an oil molecule offers no electric charge to bond it with a water molecule, and for this reason, oil and water do not mix. It is a good thing that water molecules attract each other so strongly, because this means that a great amount of energy is required to change water from a liquid to a gas. If this were not so, the oceans and rivers would vaporize, and life on Earth could not exist as it does.

**BOND ENERGY.** The last two paragraphs allude to attractions between molecules, which is not the same as (nor is it as strong as) the attraction between atoms within a molecule. In fact, the bond energy—the energy required to pull apart the atoms in a chemical bond—is low for water. This is due to the presence of hydrogen atoms, with their two (rather than eight) valence electrons. It is thus relatively easy to separate water into its constituent parts of hydrogen and oxygen, through a process known as electrolysis.

Covalent bonds that involve hydrogen are among the weakest bonds between atoms. (Again, this is different from bonds between molecules.) Stronger than hydrogen bonds are regular, octet-rule covalent bonds: as one might expect, double covalent bonds are stronger than

## KEY TERMS

**ANION:** The negative ion that results when an atom gains one or more electrons. An anion (pronounced "AN-ie-un") of an element is never called, for instance, the chlorine anion. Rather, for an anion involving a single element, it is named by adding the suffix -ide to the name of the original element—hence, "chloride." Other rules apply for more complex anions.

**ATOM:** The smallest particle of an element. 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 of elements in order of atomic number.

**BOND ENERGY:** The energy required to pull apart the atoms in a chemical bond.

**CATION:** The positive ion that results when an atom loses one or more electrons. A cation (pronounced "KAT-ie-un") is named after the element of which it is an ion and thus is called, for instance, the aluminum ion or the aluminum cation.

**CHEMICAL BONDING:** The joining, through electromagnetic force, of atoms representing different elements. The principal types of bonds are covalent bonding and ionic bonding, though few bonds are purely one or the other. Rather, there is a wide range of "hybrid" bonds, in accordance with the electronegativity values of the elements involved.

**CHEMICAL SYMBOL:** A one-or two-letter abbreviation for the name of an element.

**COMPOUND:** A substance made up of atoms of more than one element. These atoms are usually joined in molecules.

**COVALENT BONDING:** A type of chemical bonding in which two atoms share valence electrons. Atoms may bond by single, double, or triple covalent bonds, which, in representations of Lewis structures, are shown by single, double, or triple dashed lines. (The double dashed line looks like an equals sign.) When atoms have differing values of electronegativity, they form polar covalent bonds.

**DUET RULE:** A term describing the distribution of valence electrons when hydrogen atoms—which end up with only two valence electrons—experience chemical bonding with other atoms. Most other elements follow the octet rule.

**ELECTRON:** Negatively charged particles in an atom. Electrons, which spin around the protons and neutrons that make up the atom's nucleus, are essential to chemical bonding.

**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 down chemically into other substances.

## KEY TERMS CONTINUED

**ION:** An atom that has lost or gained one or more electrons, and thus has a net electrical charge. Ions may either be anions or cations.

**IONIC BONDING:** A form of chemical bonding that results from attractions between ions with opposite electrical charges.

**LEWIS STRUCTURE:** A means of showing schematically how valence electrons are distributed among the atoms in a molecule. Also known as the electron-dot system, Lewis structure represents pairs of electrons with a symbol rather like a colon, which—depending on the situation—can be placed above, below, or on either side of the chemical symbol. In the Lewis structure, the pairs of electrons involved in chemical bonds are usually represented by a dashed line.

**MOLECULE:** A group of atoms, usually, but not always, representing more than one element, joined in a structure. Compounds are typically made of up molecules.

**NEUTRON:** A subatomic particle that has no electrical 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.

**OCTET RULE:** A term describing the distribution of valence electrons that takes place in chemical bonding for most elements, which end up with eight valence electrons. Hydrogen is an exception, and follows the duet rule. A few elements follow other rules, and some (most notably the noble gases) do not typically bond with other elements.

**PERIODIC TABLE OF ELEMENTS:** A chart showing the elements arranged in order of atomic number. Vertical columns within the periodic table indicate groups or "families" of elements with similar chemical characteristics.

**POLAR COVALENT BONDING:** The type of chemical bonding between atoms that have differing values of electronegativity. If the difference is extreme, of course, the bond is not a covalent bond at all, but an ionic bond. Thus, although these are sometimes called polar bonds, they are more properly identified as polar covalent bonds.

**PROTON:** A positively charged particle in an atom.

**VALENCE ELECTRONS:** Electrons that occupy the highest energy levels in an atom. These are the only electrons involved in chemical bonding. By contrast, the core electrons, or the ones at lower energy levels, play no role in the bonding of atoms.

**VALENCY:** The property of the atom of one element that determines its ability to bond with atoms of other elements.

single ones, and triple covalent bonds are stronger still. Strongest of all are ionic bonds, involved in the bonding of a metal to a metal, or a metal to a nonmetal, as in salt. The strength of the bond energy in salt is reflected by its boiling point of 1,472°F (800°C), much higher than that of water, at 212°F (100°C).

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# COMPOUNDS

## CONCEPT

A compound is a chemical substance in which atoms combine in such a way that the compound always has the same composition, unless it is chemically altered in some way. Elements make up compounds, and although there are only about 90 elements that occur in nature, there are literally many millions of compounds. A compound is not the same as a mixture, which has a variable composition, but until chemists understood the atomic and molecular substructure of compounds, the distinction was not always clear. When atoms of one element bond to atoms of another, they form substances quite different from either element. Sugar, for instance, is made up of carbon, the material in coal and graphite, along with two gases, hydrogen and oxygen. None of these is sweet, yet when they are brought together in just the right way, they make the compound that sweetens everything from breakfast cereals to colas. A compound cannot be understood purely in terms of its constituent elements; an awareness of the structure is also needed. Likewise, it is important to know just how to name a compound, using a uniform terminology, since there are far too many substances in the world to give each an individual name.

## HOW IT WORKS

### Elements and Compounds

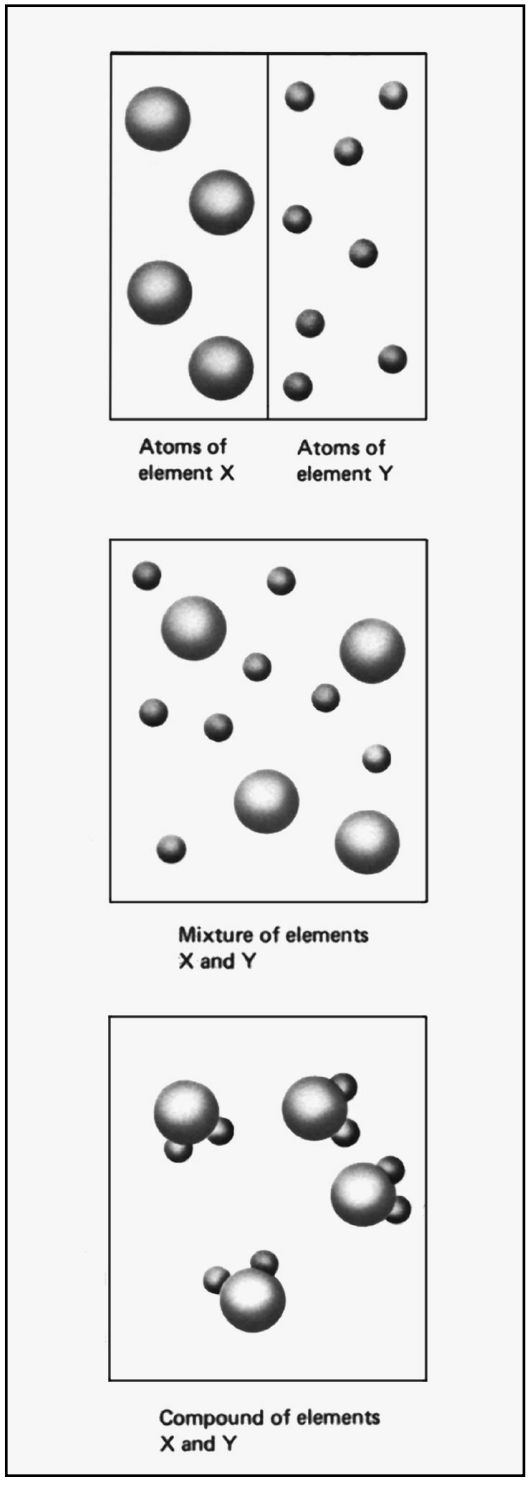
A compound is a substance made up of atoms representing more than one element, and these atoms are typically joined in molecules. The composition of a compound is always the same: for instance, water always contains molecules composed of two hydrogen atoms bonded to a single oxygen atom. It can be frozen or boiled, but the molecules themselves are unchanged, because freezing and boiling are merely physical processes. To transform one compound into another, on the other hand, requires a chemical change or reaction.

Likewise, a chemical change is required to break down a compound into its constituent elements. Water can be broken down by passing a powerful electric current through it. This process, known as electrolysis, separates water into hydrogen and oxygen, both of which are highly flammable gases. The fact that they can be joined to form water, a substance used for putting out most kinds of fires, illustrates the types of changes elements undergo when they join to form compounds.

The atoms in a compound do not change into other atoms; or to put it another way, the elements do not change into other elements. Though two hydrogen atoms bond with an oxygen atom to form water, they are still hydrogens, and the oxygen is still an oxygen. The atoms' elemental identity thus remains intact, and if these elements are separated, they can join with other elements to form entirely different compounds.

### Letters and Elements; Words and Compounds

The nature of a compound is almost paradoxical: the constituent elements remain the same, yet the compound typically bears little resemblance to the elements that form it. How can this be? Perhaps an analogy to language, and the symbols used to express it, will serve to show that this




A MIXTURE VERSUS A COMPOUND. *(Robert L. Wolke. Reproduced by permission.)*

apparent contradiction is not a contradiction at all—it is merely evidence of the complexities that occur when a simple particle contributes to a larger combination.

There are between 88 and 92 elements that appear in nature; figures vary, because a handful of the elements with atomic numbers less than 92 have not actually been found in nature, but were produced in laboratories. (All elements with an atomic number higher than that of uranium, which is 92, are artificial.) In any case, there are far more elements than there are letters in the English alphabet; yet even with 26 characters, it is possible to form an almost limitless vocabulary.

Let us focus on a single letter, *g*. Phonetically, it can make a hard sound, as in great, or a soft one, as in geranium. It may be silent, as in light, or it may combine with another letter to make either a typical "g" sound (edge) or a totally unexpected one (rough). It can slide into a vowel sound smoothly, as in singer, or with an almost imperceptible pause, as in finger. The complexities multiply when we consider the range of possibilities for the letter *g*, and all the resultant meanings involved: from God to dog, or from glory to degeneration.

**WHAT THIS ANALOGY SHOWS ABOUT CHEMISTRY.** One could go on endlessly in this vein, and all with just one letter; however, a few points need to be made regarding the analogy between letters of the alphabet and elements. First of all, in all of the examples given above, or any number of others, the *g* still remained a *g*. In the same way, an atom of hydrogen (another g-word!) is always a hydrogen, whether it combines with oxygen to form water, nitrogen to make ammonia, or carbon to produce petroleum.

Secondly, note that this illustration would have been more difficult if the letter chosen had been *q* or *z*, since these are used more rarely. Likewise, there are elements such as technetium or praseodymium that seldom come up in discussions of compounds. On the other hand, one cannot go far in the study of chemistry without running across compounds involving hydrogen, carbon, oxygen, nitrogen, various metals, or halogens such as fluorine.

A third point to consider is the fact that there is nothing about *g* itself that provides any information as to the meaning of the word it helps to form. Here the analogy to elements is imperfect, because the nature of the element's subatomic structure—particularly the configuration of electrons on the outer shell of the atom—

provides a great deal of information as to how it will combine with other atoms.

Still, it is evident, as we have seen, that the properties of a compound cannot easily be predicted by studying the properties of its constituent elements—just as one cannot begin to define a word simply because it contains a *g*. On the other hand, knowledge of the sounds that *g* makes may help us to pronounce a word containing that letter. In the same way, the fact that a compound includes carbon provides a clue that the compound might be organic.

Even when we have all the letters to form a word, we still need to know how they are ordered. Loge and ogle contain the same letters, but one is a noun referring to a theater box, whereas the other is a verb meaning the act of looking at someone in an improper fashion. In chemistry, these are called isomers: two substances having identical chemical formulas, but differing chemical structures.

It so happens that *g* is also part of the suffix -ing, used in forming a gerund. Aside from being yet another *g*-word, a gerund is a substantive, or noun form of a verb: for instance, going. Once again, there is a similarity between words and compounds. Just as certain classes of words are formed by the addition of regular suffixes, so the naming of whole classes of compounds can be achieved by means of a uniform system of nomenclature.

## REAL-LIFE APPLICATIONS

### Distinguishing Between Compounds and Mixtures

To continue the analogy used above just one step further, a word is not just a collection of letters; it has to have a meaning. Likewise, the fact that various substances are mixed together does not necessarily make them a compound. Actually, the difference between a word and a mere collection of letters is somewhat greater than the difference between a compound and a mixture—a substance in which elements are not chemically bonded, and in which the composition is variable. A nonsensical string of characters serves no linguistic purpose; on the other hand, mixtures are an integral part of life.

Tea, whether iced or hot, is a mixture. So is coffee, or even wine. In each case, substances are added together and subjected to a process, but the result is not a compound. We know this because the composition varies. Depending on the coffee beans used, for instance, coffee can have a wide variety of flavors. If, in the brewing process, too much coffee is used in proportion to the water, the resulting mixture will be strong or bitter; on the hand, an insufficient coffee-to-water ratio will produce coffee that is too weak.

Note that a number of terms have been used here that, from a scientific standpoint at least, are vague. How weak is "too weak"? That all depends on the tastes of the person making the coffee. But as long as coffee beans and hot water are used, no matter what the proportion, the mixture is still coffee. On the other hand, when two oxygen atoms, rather than one, are chemically combined with two hydrogen atoms, the result is not "strong water." Nor is it "oxygenated water": it is hydrogen peroxide, a substance no one should drink.

Three principal characteristics serve to differentiate a compound from a mixture. First, as we have seen, a compound has a definite and constant composition, whereas a mixture can exist with virtually any proportion between its constituent parts. Second, elements lose their characteristic elemental properties once they form a compound, but the parts of a mixture do not. (For example, when mixed with water, sugar is still sweet.) Third, the formation of a compound involves a chemical reaction, whereas a mixture can be created simply by the physical act of stirring items together.

### The Atomic and Molecular Keys

The means by which compounds are formed are discussed numerous times, and in various ways, throughout this book. A few of those particulars will be mentioned briefly below, in relation to the naming of compounds, but for the most part, there will be no attempt to explain the details of the processes involved in chemical bonding. The reader is therefore encouraged to consult the essays on Chemical Bonding and Electrons.

It is important, nonetheless, to recognize that chemists' knowledge is based on their understanding of the atom and the ways that electrons, negatively charged particles in the atom, bring

about bonds between elements. Awareness of these specifics emerged only at the beginning of the twentieth century, with the discovery of subatomic particles. Another important threshold had been crossed a century before, with the development of atomic theory by English chemist John Dalton (1766-1844), and of molecular theory by Italian physicist Amedeo Avogadro (1776-1856).

Around the same time, French chemists Antoine Lavoisier (1743-1794) and Joseph-Louis Proust (1754-1826), respectively, clarified the definitions of "element" and "compound." Until then, the idea of a compound had little precise meaning for chemists, who often used the term to describe a mixture. Thus, French chemist Claude Louis Berthollet (1748-1822) asserted that compounds have variable composition, and for evidence he pointed to the fact that when some metals are heated, they form oxides, in which the percentage of oxygen increases with temperature.

Proust, on the other hand, maintained that compounds must have a constant composition, an argument supported by Dalton's atomic theory. Proust worked to counter Berthollet's positions on a number of particulars, but was still unable to explain why metals form variable alloys, or combinations of metals; no chemist at the time understood that an alloy is a mixture, not a compound.

Nonetheless, Proust was right in his theory of constant composition, and Berthollet was incorrect on this score. With the discovery of subatomic structures, it became possible to develop highly sophisticated theories of chemical bonding, which in turn facilitated understanding of compounds.

## Types of Compounds

**ORGANIC COMPOUNDS.** Though there are millions of compounds, these can be grouped into just a few categories. Organic compounds, of which there are many millions, are compounds containing carbon. The only major groupings of carbon-containing compounds that are not considered organic are carbonates, such as limestone, and oxides, such as carbon dioxide. Organic compounds can be further subdivided into a number of functional groups, such as alcohols. Within the realm of organic compounds, whether natural or artificial, are petroleum and its many products, as well as plastics and other synthetic materials.

The term "organic," as applied in chemistry, does not necessarily refer to living things, since the definition is based on the presence of carbon. Nonetheless, all living organisms are organic, and the biochemical compounds in living things form an important subset of organic compounds. Biochemical compounds are, in turn, divided into four families: carbohydrates, proteins, nucleic acids, and lipids.

**INORGANIC COMPOUNDS.** Inorganic compounds can be classified according to five major groupings: acids, bases, salts, oxides, and others. An acid is a compound which, when dissolved in water, produces positive ions (atoms with an electric charge) of hydrogen. Bases are substances that produce negatively charged hydroxide ($OH^-$) ions when dissolved in water. An oxide is a compound in which the only negatively charged ion is an oxygen, and a salt is formed by the reaction of an acid with a base. Generally speaking, a salt is any combination of a metal and a nonmetal, and it can contain ions of any element but hydrogen.

The remaining inorganic compounds, classified as "others," are those that do not fit into any of the groupings described above. An important subset of this broad category are the coordination compounds, formed when one or more ions or molecules contributes both electrons necessary for a bonding pair, in order to bond with a metallic ion or atom.

## Naming Compounds

In the early days of chemistry as a science, common names were applied to compounds. Water is an example of a common name; so is sugar, as well as salt. These names work well enough in everyday life, and in fact, chemists still refer to water simply as "water." (The only other common name still used in chemistry is ammonia.)

But as the number of compounds discovered and developed by chemists began to proliferate, the need for a systematic means of naming them became apparent. With millions of compounds, it would be nearly impossible to come up with names for every one. Furthermore, common names tell chemists nothing about the chemical properties of a particular substance.

Today, chemists use a system of nomenclature that is rather detailed but fairly easy to understand, once the rules are understood. We will examine this system briefly, primarily as it relates to binary compounds—compounds containing just two elements. Binary compounds are divided into three groups. The first two are ionic compounds, involving metals that form positively charged ions, or cations (pronounced KAT-ie-unz). The third consists of compounds that contain only nonmetals. These groups are:

- Type I: Ionic compounds involving a metal that always forms a cation of a certain electric charge.
- Type II: Ionic compounds involving a metal (typically a transition metal) that forms cations with differing charges.
- Type III: Compounds containing only nonmetals.

**CATIONS AND ANIONS.** Cations are represented symbolically thus: $H^+$, or $Mg^{2+}$. The first, a hydrogen cation, has a positive charge of 1, but note that the 1 is not shown—just as the first power of a number is never designated in mathematics. In the second example, a magnesium cation, the superscript number, combined with the plus sign (which can either follow the number, as is shown here, or proceed it) indicates that the atom has a positive charge of two. Thus, even if one were not told that this is a cation, it would be easy enough to discern from the notation.

Anions (AN-ie-unz), or negatively charged ions, are represented in a similar way: $H^-$ for hydride, an anion of hydrogen; or $O^{2-}$ for oxide. Note, however, that the naming of anions and cations is different. Cations are always called, for example, a hydrogen cation, or a magnesium cation. On the other hand, names of simple anions (involving a single atom) are formed by taking the root of the element name and adding an -ide: for example, fluoride ($F^-$).

**TYPE I BINARY COMPOUNDS.** In a binary ionic compound, a metal combines with a nonmetal. The metal loses one or more electrons to become a cation, while the nonmetal gains one or more electrons to become an anion. Thus, table salt is formed by the joining of a cation of the metal sodium ($Na^+$) and an anion of the nonmetal chlorine ($Cl^-$). Instead of the common name "salt," which can apply to a range of substances, its chemical name is sodium chloride.

In naming Type I binary compounds, of which sodium chloride is an example, the cation is always represented first by the name of the element. The anion follows, with the root name of the element attached to the -ide suffix, as described above. Another example is calcium sulfide, formed by a cation of the metal calcium ($Ca^{2+}$) and an anion of the nonmetal sulfur ($S^{2-}$).

**TYPE II BINARY COMPOUNDS.** The chemical nomenclature for type II binary compounds is somewhat more complicated, because they involve metals that can have multiple positive charges. This is particularly true of the transition metals, a family of 40 elements in the middle of the periodic table distinguished from other elements by a number of characteristics. The name "transition" thus implies a break in the even pattern of the periodic table.

Iron (Fe), for instance, is a transition metal, and it can form cations with charges of 2+ or 3+, while copper (Cu) can form cations with charges of 1+ or 2+. When encountering positively charged cations, it is not enough to say, for instance, "iron oxide," or "copper sulfide," because it is not clear which iron cation is involved. To solve the problem, chemists use a system of Roman numerals.

According to this system, the cations referred to above are expressed in the name of a Type II binary compound thus: iron (II), iron (III), copper (I), and copper (II). This is followed with the name of the anion, as before, using the -ide suffix. Note that the Roman numeral is usually the same as the number of positive charges in the cation.

It should be noted, also, that there is an older system for naming Type II binary compounds with terms that incorporate the element name—often the Latin original, reflected in the chemical symbol—with a suffix. For instance, this system uses the word "ferrous" for iron (II) and "ferric" for iron (III). However, this method of nomenclature is increasingly being replaced by the one we have described here.

**TYPE III BINARY COMPOUNDS.** In a Type III binary compound involving only nonmetals, the first element in the formula is referred to simply by its element name, as though it were a cation, while the second element is given an -ide suffix, as though it were an anion. If there

is more than one atom present, prefixes are used to indicate the number of atoms. These prefixes are listed below. It should be noted that mono- is never used for naming the first element in a type III binary compound.

- mono-: 1
- di-: 2
- tri-: 3
- tetra-: 4
- penta-: 5
- hexa-: 6
- hepta-: 7
- octa-: 8

Thus $CO_2$ is called carbon dioxide, indicating one carbon atom and two oxygens. Again, mono- is not used for the first element, but it is used for the second: hence, the name of the compound with the formula CO is carbon monoxide. It is also possible to know the formula for a compound simply from the name: if confronted with a name such as "dinitrogen pentoxide," for instance, it is fairly easy to apply the rules governing these prefixes to discern that the substance is $N_2O_5$. Note that vowels at the end of a prefix are dropped when the name of the element that follows it also begins with a vowel: we say monoxide, not "monooxide"; and pentoxide, not "pentaoxide." This makes pronunciation much easier.

**POLYATOMIC IONS AND ACIDS.** More complicated rules apply for polyatomic ions, which are charged groupings of atoms such as $NH_4NO_3$, or ammonium nitrate. The only way to learn how to name polyatomic ions is by memorizing the names of the constituent parts. In the above example, for instance, the first part of the formula, which has a positive charge, is always called ammonium, while the second part, which has a negative charge, is always called nitrate. A good chemistry textbook should provide a table listing the names of common polyatomic ions.

A number of polyatomic ions are called oxyanions, meaning that they include varying numbers of oxygen atoms combined with atoms of other elements. There are rules for designating the names of these polyatomic ions, some of which are listed in the essay on Ions and Ionization.

Still other rules govern the naming of acids; here again, the operative factor is the presence of oxygen. Thus, if the anion does not contain oxygen, the name of the acid is created by adding the prefix hydro- and the suffix -ic, as in hydrochloric acid. If the anion does contain oxygen, the root name of the principal element is joined to a suffix: depending on the relative numbers of oxygen atoms, this may be -ic or -ous.

## Isomers

As observed much earlier, isomers are like two words with the same letters, but arranged in different ways. Specifically, isomers are chemical compounds having the same formula, but in which the atoms are arranged differently, thereby forming different compounds. There are two principal types of isomer: structural isomers, which differ according to the attachment of atoms on the molecule, and stereoisomers, which differ according to the locations of the atoms in space.

An example of structural isomerism is the difference between propyl alcohol and isopropyl (rubbing) alcohol: these two have differing properties, because their alcohol functional groups are not attached to the same carbon atom in the carbon chain to which the functional group is attached.

In a stereoisomer, on the other hand, atoms are attached in the same order, but have different spatial relationships. If functional groups are aligned on the same side of a double bond between two carbon atoms, this is called a cis isomer, from a Latin word meaning "on this side." If they are on opposite sides, it is called a trans ("across") isomer. Hence the term "trans fats," which are saturated fats that improve certain properties of foods—including taste—but which may contribute to heart disease.

## WHERE TO LEARN MORE

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## KEY TERMS

**ACID:** An inorganic compound that, when dissolved in water, produces positive ions—that is, cations—of hydrogen, designated symbolically as $H^+$ ions. (This is just one definition; see Acids and Bases; Acid-Base Reactions for more.)

**ANION:** The negatively charged ion that results when an atom gains one or more electrons. The word is pronounced "AN-ie-un."

**BASE:** An inorganic compound that produces negative hydroxide ions when it is dissolved in water. These anions are designated by the symbol $OH^-$. (This is just one definition; see Acids and Bases; Acid-Base Reactions for more.)

**BINARY COMPOUND:** A compound that contains just two elements. For the purposes of establishing compound names, binary compounds are divided into Type I, Type II, and Type III.

**CATION:** The positively charged ion that results when an atom loses one or more electrons. The word "cation" is pronounced "KAT-ie-un."

**CHEMICAL BONDING:** The joining, through electromagnetic force, of atoms representing different elements.

**COMPOUND:** A substance made up of atoms of more than one element, which are chemically bonded and usually joined in molecules. The composition of a compound is always the same, unless it is changed chemically.

**COORDINATION COMPOUNDS:** Inorganic compounds formed when one or more ions or molecules contribute both electrons necessary for a bonding pair in order to bond with a metallic ion or atom.

**ELECTRON:** A negatively charged particle in an atom.

**INORGANIC COMPOUND:** For the most part, inorganic compounds are any compounds that do not contain carbon. However, carbonates and carbon oxides are also inorganic compounds. Compare with organic compounds.

**ION:** An atom or group of atoms that has lost or gained one or more electrons, and thus has a net electric charge.

**IONIC BONDING:** A form of chemical bonding that results from attractions between ions with opposite electric charges.

**IONIC COMPOUND:** A compound in which ions are present. Ionic compounds contain at least one metal joined to another element by an ionic bond.

**ISOMERS:** Substances which have the same chemical formula, but which have different chemical properties due to differences in the arrangement of atoms.

**MIXTURE:** A substance in which elements are not chemically bonded, and in which the composition is variable. A mixture is distinguished from a compound.

**ORGANIC COMPOUND:** Generally speaking, a compound containing carbon. The only exceptions are the carbonates (for example, calcium carbonate or limestone) and oxides, such as carbon dioxide.

**OXIDE:** An inorganic compound in which the only negatively charged ion is an oxygen.

## KEY TERMS CONTINUED

**SALT:** An inorganic compound formed by the reaction of an acid with a base. Generally speaking, a salt is a combination of a metal and a nonmetal, and it can contain ions of any element but hydrogen.

**TYPE I BINARY COMPOUNDS:** Ionic compounds involving a metal that always forms a cation of a certain electric charge.

**TYPE II BINARY COMPOUNDS:** Ionic compounds involving a metal (typically a transition metal) that forms cations with differing charges.

**TYPE III BINARY COMPOUNDS:** Compounds containing only nonmetals.

**VALENCE ELECTRONS:** Electrons that occupy the highest energy levels in an atom. These are the only electrons involved in chemical bonding.

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# CHEMICAL REACTIONS

## CONCEPT

If chemistry were compared to a sport, then the study of atomic and molecular properties, along with learning about the elements and how they relate on the periodic table, would be like going to practice. Learning about chemical reactions, which includes observing them and sometimes producing them in a laboratory situation, is like stepping out onto the field for the game itself. Just as every sport has its "vocabulary"—the concepts of offense and defense, as well as various rules and strategies—the study of chemical reactions involves a large set of terms. Some aspects of reactions may seem rather abstract, but the effects are not. Every day, we witness evidence of chemical reactions—for instance, when a fire burns, or metal rusts. To an even greater extent, we are surrounded by the products of chemical reactions: the colors in the clothes we wear, or artificial materials such as polymers, used in everything from nylon running jackets to plastic milk containers.

## HOW IT WORKS

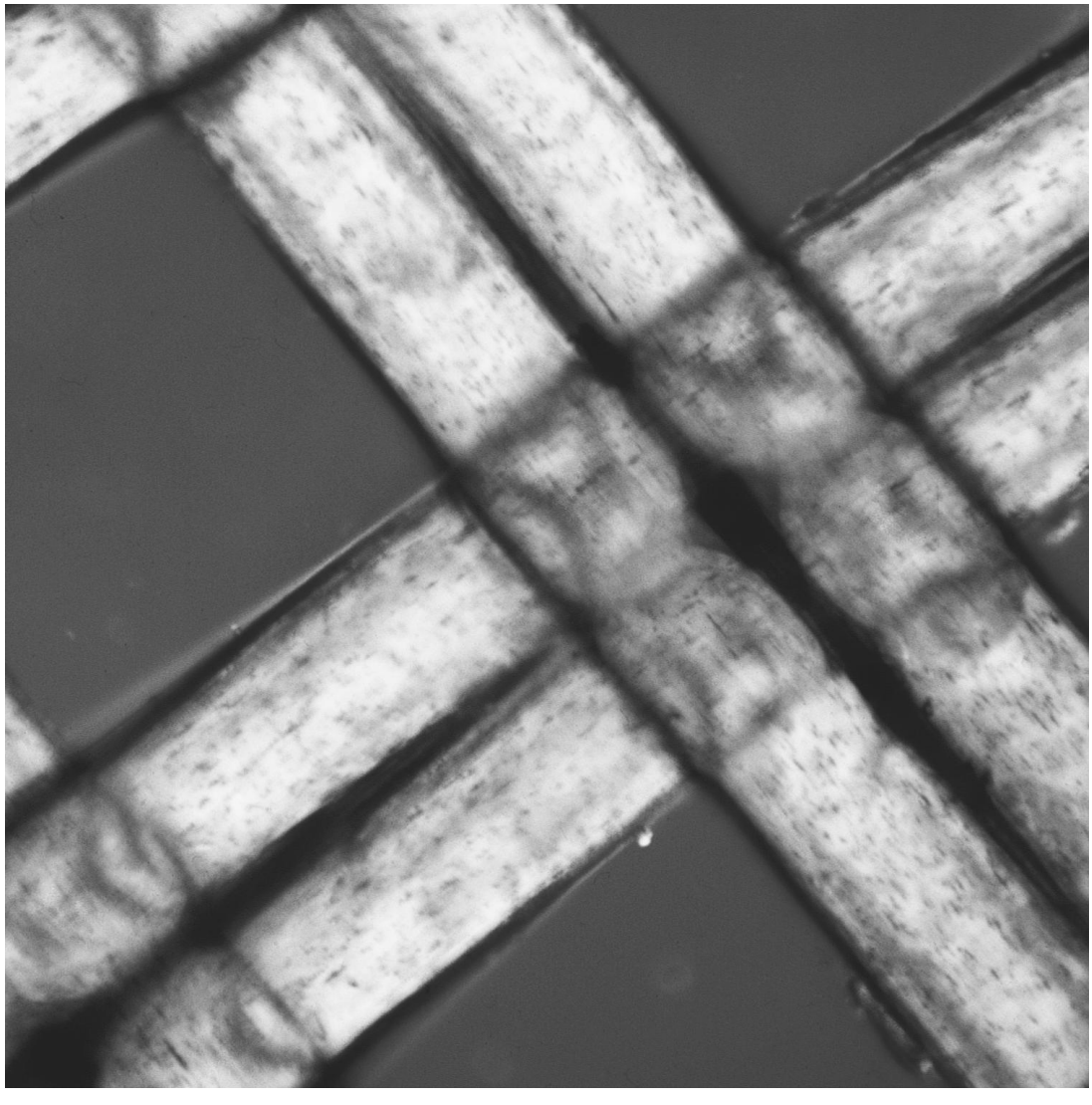
### What Is a Chemical Reaction?

If liquid water is boiled, it is still water; likewise frozen water, or ice, is still water. Melting, boiling, or freezing simply by the application of a change in temperature are examples of physical changes, because they do not affect the internal composition of the item or items involved. A chemical change, on the other hand, occurs when the actual composition changes—that is, when one substance is transformed into another. Water can be chemically changed, for instance, when an electric current is run through a sample, separating it into oxygen and hydrogen gas.

Chemical change requires a chemical reaction, a process whereby the chemical properties of a substance are altered by a rearrangement of the atoms in the substance. Of course we cannot see atoms with the naked eye, but fortunately, there are a number of clues that tell us when a chemical reaction has occurred. In many chemical reactions, for instance, the substance may experience a change of state or phase—as for instance when liquid water turns into gaseous oxygen and hydrogen as a result of electrolysis.

**HOW DO WE KNOW WHEN A CHEMICAL REACTION HAS OCCURRED?** Changes of state may of course be merely physical—as for example when liquid water is boiled to form a vapor. (These and other examples of physical changes resulting from temperature changes are discussed in the essays on Properties of Matter; Temperature and Heat.) The vapor produced by boiling water, as noted above, is still water; on the other hand, when liquid water is turned into the elemental gases hydrogen and oxygen, a more profound change has occurred.

Likewise the addition of liquid potassium chromate ($K_2CrO_4$) to a solution of barium nitrate ($Ba[NO_3]_2$ forms solid barium chromate ($BaCrO_4$). In the reaction described, a solution is also formed, but the fact remains that the mixture of two solids has resulted in the formation of a solid in a different solution. Again, this is a far more complex phenomenon than the mere freezing of water to form ice: here the fundamental properties of the materials involved have changed.



A microscopic close-up of nylon fibers. Nylon is formed through a synthesis reaction. *(Science Pictures Limited/Corbis. Reproduced by permission.)*

The physical change of water to ice or steam, of course, involves changes in temperature; likewise, chemical changes are often accompanied by changes in temperature, the crucial difference being that these changes are the result of alterations in the chemical properties of the substances involved. Such is the case, for instance, when wood burns in the presence of oxygen: once wood is turned to ash, it has become an entirely different mixture than it was before. Obviously, the ashes cannot be simply frozen to turn them back into wood again. This is an example of an irreversible chemical reaction.

Chemical reactions may also involve changes in color. In specific proportions and under the right conditions, carbon—which is black—can be combined with colorless hydrogen and oxygen to produce white sugar. This suggests another kind of change: a change in taste. (Of course, not every product of a chemical reaction should be tasted—some of the compounds produced may be toxic, or at the very least, extremely unpleasant to the taste buds.) Smell, too, can change. Sulfur is odorless in its elemental form, but when combined with hydrogen to form hydrogen sulfide ($H_2S$), it becomes an evil-smelling, highly toxic gas.

The bubbling of a substance is yet another clue that a chemical reaction has occurred. Though water bubbles when it boils, this is mere-

ly because heat has been added to the water, increasing the kinetic energy of its molecules. But when hydrogen peroxide bubbles when exposed to oxygen, no heat has been added. As with many of the characteristics of a chemical reaction described above, bubbling does not always occur when two chemicals react; however, when one of these clues is present, it tells us that a chemical reaction may have taken place.

## REAL-LIFE APPLICATIONS

### Chemical Equations

In every chemical reaction, there are participants known as reactants, which, by chemically reacting to one another, result in the creation of a product or products. As stated earlier, a chemical reaction involves changes in the arrangement of atoms. The atoms in the reactants (or, if the reactant is a compound, the atoms in its molecules) are rearranged. The atomic or molecular structure of the product is different from that of either reactant.

Note, however, that the number of atoms does not change. Atoms themselves are neither created nor destroyed, and in a chemical reaction, they merely change partners, or lose partners altogether as they return to their elemental form. This is a critical principle in chemistry, one that proves that medieval alchemists' dream of turning lead into gold was based on a fallacy. Lead and gold are both elements, meaning that each has different atoms. To imagine a chemical reaction in which one becomes the other is like saying "one plus one equals one."

**SYMBOLS IN A CHEMICAL EQUATION.** In a mathematical equation, the sums of the numbers on one side of the equals sign must be the same as the sum of the numbers on the other side. The same is true of a chemical equation, a representation of a chemical reaction in which the chemical symbols on the left stand for the reactants, and those on the right are the product or products. Instead of an equals sign separating them, an arrow, pointing to the right to indicate the direction of the reaction, is used.

Chemical equations usually include notation indicating the state or phase of matter for the reactants and products. These symbols are as follows:

- *(s)*: solid
- *(l)*: liquid
- *(g)*: gas
- *(aq)*: dissolved in water (an aqueous solution)

The fourth symbol, of course, does not indicate a phase of matter per se (though obviously it appears to be a liquid); but as we shall see, aqueous solutions play a role in so many chemical reactions that these have their own symbol. At any rate, using this notation, we begin to symbolize the reaction of hydrogen and oxygen to form water thus: $H(g) + O(g) \rightarrow H_2O(l)$.

This equation as written, however, needs to be modified in several ways. First of all, neither hydrogen nor oxygen is monatomic. In other words, in their elemental form, neither appears as a single atom; rather, these form diatomic (two-atom) molecules. Therefore, the equation must be rewritten as $H_2(g) + O_2(g) \rightarrow H_2O(l)$. But this is still not correct, as a little rudimentary analysis will show.



A CLOSE-UP OF RUST ON A PIECE OF METAL. RUST IS AN EXAMPLE OF A COMBINATION REACTION, NOT A DECOMPOSITION REACTION. *(Marko Modic/Corbis. Reproduced by permission.)*

## Balancing Chemical Equations

When checking a chemical equation, one should always break it down into its constituent elements, to determine whether all the atoms on the left side reappear on the right side; otherwise, the result may be an incorrect equation, along the lines of "1 + 1 = 1." That is exactly what has happened here. On the left side, we have two hydrogen atoms and two oxygen atoms; on the right side, however, there is only one oxygen atom to go with the two hydrogens.

Obviously, this equation needs to be corrected to account for the second oxygen atom, and the best way to do that is to show a second water molecule on the right side. This will be represented by a 2 before the $H_2O$, indicating that two water molecules now have been created. The 2, or any other number used for showing more than one of a particular chemical species in a chemical equation, is called a coefficient. Now we have $H_2(g) + O_2(g) \rightarrow 2H_2O(l)$.

Is this right? Once again, it is time to analyze the equation, to see if the number of atoms on the left equals the number on the right. Such analysis can be done in a number of ways: for instance, by symbolizing each chemical species as a circle with chemical symbols for each element in it. Thus a single water molecule would be shown as a circle containing two H's and one O.

Whatever the method used, analysis will reveal that the problem of the oxygen imbalance has been solved: now there are two oxygens on the left, and two on the right. But solving that problem has created another, because now there are four hydrogen atoms on the right, as compared with two on the left. Obviously, another coefficient of 2 is needed, this time in front of the hydrogen molecule on the left. The changed equation is thus written as: $2H_2(g) + O_2(g) \rightarrow 2H_2O(l)$. Now, finally, the equation is correct.

**The process of balancing chemical equations.** What we have done is to balance an unbalanced equation. An unbalanced equation is one in which the numbers of atoms on the left are not the same as the number of atoms on the right. Though an unbalanced equation is incorrect, it is sometimes a necessary step in the process of finding the balanced equation—one in which the number of atoms in the reactants and those in the product are equal.

In writing and balancing a chemical equation, the first step is to ascertain the identities, by formula, of the chemical species involved, as well as their states of matter. After identifying the reactants and product, the next step is to write an unbalanced equation. After that, the unbalanced equation should be subjected to analysis, as demonstrated above.

The example used, of course, involves a fairly simple substance, but often, much more complex molecules will be part of the equation. In performing analysis to balance the equation, it is best to start with the most complex molecule, and determine whether the same numbers and proportions of elements appear in the product or products. After the most complicated molecule has been dealt with, the second-most complex can then be addressed, and so on.

Assuming the numbers of atoms in the reactant and product do not match, it will be necessary to place coefficients before one or more chemical species. After this has been done, the equation should again be checked, because as we have seen, the use of a coefficient to straighten out one discrepancy may create another. Note that only coefficients can be changed; the formulas of the species themselves (assuming they were correct to begin with) should not be changed.

After the equation has been fully balanced, one final step is necessary. The coefficients must be checked to ensure that the smallest integers possible have been used. Suppose, in the above exercise, we had ended up with an equation that looked like this: $12H_2(g) + 6O_2(g) \rightarrow 12H_2O(l)$. This is correct, but not very "clean." Just as a fraction such as 12/24 needs to be reduced to its simplest form, 1/2, the same is true of a chemical equation. The coefficients should thus always be the smallest number that can be used to yield a correct result.

## Types of Chemical Reactions

Note that in chemical equations, one of the symbols used is *(aq)*, which indicates a chemical species that has been dissolved in water—that is, an aqueous solution. The fact that this has its own special symbol indicates that aqueous solutions are an important part of chemistry. Examples of reactions in aqueous solutions are discussed, for instance, in the essays on Acid-Base Reactions; Chemical Equilibrium; Solutions.

Another extremely important type of reaction is an oxidation-reduction reaction. Sometimes called a redox reaction, an oxidation-reduction reaction occurs during the transfer of electrons. The rusting of iron is an example of an oxidation-reduction reaction; so too is combustion. Indeed, combustion reactions—in which oxygen produces energy so rapidly that a flame or even an explosion results—are an important subset of oxidation-reduction reactions.

**REACTIONS THAT FORM WATER, SOLIDS, OR GASES.** Another type of reaction is an acid-base reaction, in which an acid is mixed with a base, resulting in the formation of water along with a salt.

Other reactions form gases, as for instance when water is separated into hydrogen and oxygen. Similarly, heating calcium carbonate (limestone) to make calcium oxide or lime for cement also yields gaseous carbon dioxide: $CaCO^{3}(s)$ + heat $\rightarrow CaO(s) + CO^{2}(g)$.

There are also reactions that form a solid, such as the one mentioned much earlier, in which solid $BaCrO_4(s)$ is formed. Such reactions are called precipitation reactions. But this is also a reaction in an aqueous solution, and there is another product: $2KNO_3(aq)$, or potassium nitrate dissolved in water.

**SINGLE AND DOUBLE DISPLACEMENT.** The reaction referred to in the preceding paragraph also happens to be an example of another type of reaction, because two anions (negatively charged ions) have been exchanged. Initially $K^+$ and $CrO_4^{2-}$ were together, and these reacted with a compound in which $Ba^{2+}$ and $NO_3^-$were combined. The anions changed places, an instance of a double-displacement reaction, which is symbolized thus: AB + CD $\rightarrow$AD + CB.

It is also possible to have a single-displacement reaction, in which an element reacts with a compound, and one of the elements in the compound is released as a free element. This can be represented symbolically as A + BC $\rightarrow$B + AC. Single-displacement reactions often occur with metals and with halogens. For instance, a metal (A) reacts with an acid (BC) to produce hydrogen (B) and a salt (AC).

**COMBINATION AND DECOMPOSITION.** A synthesis, or combination, reaction is one in which a compound is formed from simpler materials—whether those materials be elements or simple compounds. A basic example of this is the reaction described earlier in relation to chemical equations, when hydrogen and oxygen combine to form water. On the other hand, some extremely complex substances, such as the polymers in plastics and synthetic fabrics such as nylon, also involve synthesis reactions.

When iron rusts (in other words, it oxidizes in the presence of air), this is both an oxidation-reduction and a synthesis reaction. This also represents one of many instances in which the language of science is quite different from everyday language. If a piece of iron—say, a railing on a balcony—rusts due to the fact that the paint has peeled off, it would seem from an unscientific standpoint that the iron has "decomposed." However, rust (or rather, metal oxide) is a more complex substance than the iron, so this is actually a synthesis or combination reaction.

A true decomposition reaction occurs when a compound is broken down into simpler compounds, or even into elements. When water is subjected to electrolysis such that the hydrogen and oxygen are separated, this is a decomposition reaction. The fermentation of grapes to make wine is also a form of decomposition.

And then, of course, there are the processes that normally come to mind when we think of "decomposition": the decay or rotting of a formerly living thing. This could also include the decay of something, such as an item of food, made from a formerly living thing. In such instances, an organic substance is eventually broken down through a number of processes, most notably the activity of bacteria, until it ultimately becomes carbon, nitrogen, oxygen, and other elements that are returned to the environment.

**SOME OTHER PARAMETERS.** Obviously, there are numerous ways to classify chemical reactions. Just to complicate things a little more, they can also be identified as to whether they produce heat (exothermic) or absorb heat (endothermic). Combustion is clearly an example of an exothermic reaction, while an endothermic reaction can be exemplified by the process that takes place in a cold pack. Used for instance to prevent swelling on an injured ankle, a cold pack contains an ampule that absorbs heat when broken.

Still another way to identify chemical reactions is in terms of the phases of matter involved.

We have already seen that some reactions form gases, some solids, and some yield water as one of the products. If reactants in one phase of matter produce a substance or substances in the same phase (liquid, solid, or gas), this is called a homogeneous reaction. On the other hand, if the reactants are in different phases of matter, or if they produce a substance or substances that are in a different phase, this is called a heterogeneous reaction.

An example of a homogeneous reaction occurs when gaseous nitrogen combines with oxygen, also a gas, to produce nitrous oxide, or "laughing gas." Similarly, nitrogen and hydrogen combine to form ammonia, also a gas. But when hydrogen and oxygen form water, this is a heterogeneous reaction. Likewise, when a metal undergoes an oxidation-reduction reaction, a gas and a solid react, resulting in a changed form of the metal, along with the production of new gases.

Finally, a chemical reaction can be either reversible or irreversible. Much earlier, we described how wood experiences combustion, resulting in the production of ash. This is clearly an example of an irreversible reaction. The atoms in the wood and the air that oxidized it have not been destroyed, but it would be impossible to put the ash back together to make a piece of wood. By contrast, the formation of water by hydrogen and oxygen is reversible by means of electrolysis.

**KEEPING IT ALL STRAIGHT.** The different classifications of reactions discussed above are clearly not mutually exclusive; they simply identify specific aspects of the same thing. This is rather like the many physical characteristics that describe a person: gender, height, weight, eye color, hair color, race, and so on. Just because someone is blonde, for instance, does not mean that the person cannot also be brown-eyed; these are two different parameters that are more or less independent.

On the other hand, there is some relation between these parameters in specific instances: for example, females over six feet tall are rare, simply because women tend to be shorter than men. But there are women who are six feet tall, or even considerably taller. In the same way, it is unlikely that a reaction in an aqueous solution will be a combustion reaction—yet it does happen, as for instance when potassium reacts with water.

## Studying Chemical Reactions

Several aspects or subdisciplines of chemistry are brought to bear in the study of chemical reactions. One is stoichiometry (stoy-kee-AH-muh-tree), which is concerned with the relationships among the amounts of reactants and products in a chemical reaction. The balancing of the chemical equation for water earlier in this essay is an example of basic stoichiometry.

Chemical thermodynamics is the area of chemistry that addresses the amounts of heat and other forms of energy associated with chemical reactions. Thermodynamics is also a branch of physics, but in that realm, it is concerned purely with physical processes involving heat and energy. Likewise physicists study kinetics, associated with the movement of objects. Chemical kinetics, on the other hand, involves the study of the collisions between molecules that produce a chemical reaction, and is specifically concerned with the rates and mechanisms of reaction.

**SPEEDING UP A CHEMICAL REACTION.** Essentially, a chemical reaction is the result of collisions between molecules. According to this collision model, if the collision is strong enough, it can break the chemical bonds in the reactants, resulting in a rearrangement of the atoms to form products. The more the molecules collide, the faster the reaction. Increase in the numbers of collisions can be produced in two ways: either the concentrations of the reactants are increased, or the temperature is increased. In either case, more molecules are colliding.

Increases of concentration and temperature can be applied together to produce an even faster reaction, but rates of reaction can also be increased by use of a catalyst, a substance that speeds up the reaction without participating in it either as a reactant or product. Catalysts are thus not consumed in the reaction. One very important example of a catalyst is an enzyme, which speeds up complex reactions in the human body. At ordinary body temperatures, these reactions are too slow, but the enzyme hastens them along. Thus human life can be said to depend on chemical reactions aided by a wondrous form of catalyst.

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## KEY TERMS

**ACID-BASE REACTION:** A chemical reaction in which an acid is mixed with a base, resulting in the formation of water along with a salt.

**AQUEOUS SOLUTIONS:** A mixture of water and any substance that is solvent in it.

**BALANCED EQUATION:** A chemical equation in which the numbers of atoms in the reactants and those in the product are equal. In the course of balancing an equation, coefficients may need to be applied to one or more of the chemical species involved; however, the actual formulas of the species cannot be changed.

**CATALYST:** A substance that speeds up a chemical reaction without participating in it either as a reactant or product. Catalysts are thus not consumed in the reaction.

**CHEMICAL EQUATION:** A representation of a chemical reaction in which the chemical symbols on the left stand for the reactants, and those on the right for the product or products. On paper, a chemical equation looks much like a mathematical one; however, instead of an equals sign, a chemical equation uses an arrow to show the direction of the reaction.

**CHEMICAL KINETICS:** the study of the rate at which chemical reactions occur.

**CHEMICAL REACTION:** A process whereby the chemical properties of a substance are changed by a rearrangement of the atoms in the substance.

**CHEMICAL SPECIES:** A generic term used for any substance studied in chemistry—whether it be an element, compound, mixture, atom, molecule, ion, and so forth.

**CHEMICAL THERMODYNAMICS:** The study of the amounts of heat and other forms of energy associated with chemical reactions.

**COEFFICIENT:** A number used to indicate the presence of more than one unit—typically, more than one molecule—of a chemical species in a chemical equation. For instance, $2H_2O$ indicates two water molecules. (Note that 1 is never used as a coefficient.)

**COLLISION MODEL:** The theory that chemical reactions are the result of collisions between molecules that are strong enough to break bonds in the reactants, resulting in a rearrangement of atoms to form a product or products.

**DECOMPOSITION REACTION:** A chemical reaction in which a compound is broken down into simpler compounds, or even into elements. This is the opposite of a synthesis or combination reaction.

**DOUBLE-DISPLACEMENT REACTION:** A chemical reaction in which the partners in two compounds change places. This can be symbolized as AB + CD →AD + CB. Compare single-displacement reaction.

**ENDOTHERMIC:** A term describing a chemical reaction in which heat is absorbed or consumed.

**EXOTHERMIC:** A term describing a chemical reaction in which heat is produced.

## KEY TERMS CONTINUED

**HETEROGENEOUS:** A term describing a chemical reaction in which the reactants are in different phases of matter (liquid, solid, or gas), or one in which the product is in a different phase from that of the reactants.

**HOMOGENEOUS:** A term describing a chemical reaction in which the reactants and the product are all in the same phase of matter (liquid, solid, or gas).

**OXIDATION-REDUCTION REACTION:** A chemical reaction involving the transfer of electrons.

**PRECIPITATION REACTION:** A chemical reaction in which a solid is formed.

**PRODUCT:** The substance or substances that result from a chemical reaction.

**REACTANT:** A substance that interacts with another substance in a chemical reaction, resulting in the formation of a product.

**SINGLE-DISPLACEMENT REACTION:** A chemical reaction in which an element reacts with a compound, and one of the elements in the compound is released as a free element. This can be represented symbolically as $A + BC \rightarrow B + AC$. Compare double-displacement reaction.

**STOICHIOMETRY:** The study of the relationships among the amounts of reactants and products in a chemical reaction. Producing a balanced equation requires application of stoichiometry (pronounced "stoy-kee-AH-muh-tree").

**SYNTHESIS OR COMBINATION REACTION:** A chemical reaction in which a compound is formed from simpler materials—either elements or simple compounds. It is the opposite of a decomposition reaction.

**UNBALANCED EQUATION:** A chemical equation in which the sum of atoms in the product or products does not equal the sum of atoms in the reactants. Initial observations of a chemical reaction usually produce an unbalanced equation, which needs to be analyzed and corrected (by the use of coefficients) to yield a balanced equation.

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# OXIDATION-REDUCTION REACTIONS

## CONCEPT

Most people have heard the term "oxidation" at some point or another, and, from the sound of the word, may have developed the impression that it has something to do with oxygen. Indeed it does, because oxygen has a tendency to draw electrons to itself. This tendency, rather than the presence of oxygen itself, is actually what identifies oxidation, defined as a process in which a substance loses electrons. The oxidation of one substance is always accompanied by reduction, or the gaining of electrons, on the part of another substance—hence the term "oxidation-reduction reaction," sometimes called a redox reaction. The world is full of examples of this highly significant form of chemical reaction. One such example is combustion, or an even more rapid form of combustion, explosion. Likewise the metabolism of food, as well as other biological processes, involves oxidation and reduction reactions. So, too, do a number of processes that take place on the surfaces of metals: when iron rusts; when copper turns green; or when aluminum forms a coating of aluminum oxide that prevents it from rusting. Oxidation-reduction reactions also play a major role in electrochemistry, which has a highly useful application to daily life in the form of batteries.

## HOW IT WORKS

### Chemical Reactions

A chemical reaction is a process whereby the chemical properties of a substance are changed by a rearrangement its atoms. The change produced by a chemical reaction is quite different from a purely physical change, which does not affect the fundamental properties of the substance itself. A piece of copper can be heated, melted, beaten into different shapes, and so forth, yet throughout all those changes, it remains pure copper, an element of the transition metals family.

But suppose a copper roof is exposed to the elements for many years. Copper is famous for its highly noncorrosive quality, and this, combined with its beauty, has made it a favored material for use in the roofs of imposing buildings. (Because it is relatively expensive, few middle-class people today can afford a roof entirely made of copper, but sometimes it is used as a decorative touch—for instance, over the entryway of a house.) Eventually, however, copper does begin to corrode when exposed to air for long periods of time.

Over the years, exposed copper develops a thin layer of black copper oxide, and as time passes, traces of carbon dioxide in the air contribute to the formation of greenish copper carbonate. This explains why the Statue of Liberty, covered in sheets of copper, is green, rather than having the reddish-golden hue of new, uncorroded copper.

**EXTERNAL VS. INTERNAL CHANGE.** The preceding paragraphs describe two very different phenomena. The first was a physical change in which the chemical properties of a substance—copper—remained unaltered. The second, on the other hand, involved a chemical change on the surface of the copper, as copper atoms bonded with carbon and oxygen atoms in the air to form something different from copper. The difference between these two types of changes can be likened to varieties of changes in a person's life—an external change

on the one hand, and a deeply rooted change on the other.

A person may move to another house, job, school, or town, yet the person remains the same. Many sayings in the English language express this fact: for instance, "Wherever you go, there you are," or "You can take the boy out of the country, but you can't take the country out of the boy." Moving is simply a physical change. On the other hand, if a person changes belief systems, overcomes old feelings (or succumbs to new ones), changes lifestyles in a profound manner, or in any other way changes his or her mind about something important—this is analogous to a chemical change. In these instances, the person, like the surface of the copper described above, has changed not merely in external properties, but in inner composition.

## "LEO the Lion Says 'GER'"

Chemical reactions are addressed in depth within the essay devoted to that subject, which discusses—among other subjects—many ways of classifying chemical reactions. These varieties of chemical reaction are not all mutually exclusive, as they relate to different aspects of the reaction. As noted in the review of various reaction types, one of the most significant is an oxidation-reduction reaction (sometimes called a redox reaction) involving the transfer of electrons.

As its name implies, an oxidation-reduction reaction is really two processes: oxidation, in which electrons are lost, and reduction, in which electrons are gained. Though these are defined separately here, they do not occur independently; hence the larger reaction of which each is a part is called an oxidation-reduction reaction. In order to keep the two straight, chemistry teachers long ago developed a useful, if nonsensical, mnemonic device: "LEO the lion says 'GER'." LEO stands for "Loss of Electrons, Oxidation," and "GER" means "Gain of Electrons, Reduction."

Many, though not all, oxidation-reduction reactions involve oxygen. Oxygen combines readily with other elements, and in so doing, it tends to grab electrons from those other elements' atoms. As a result, the oxygen atom becomes an ion (an atom with an electric charge)—specifically, an anion, or negatively charged ion.

In interacting with another element, oxygen becomes reduced, while the other element is oxidized to become a cation, or a positively charged ion. This, too, is easy to remember: oxygen itself, obviously, cannot be oxidized, so it must be the one being reduced. But since not all oxidation-reduction reactions involve oxygen, perhaps the following is a better way to remember it. Electrons are negatively charged, and the element that takes them on in an oxidation-reduction reaction is reduced—just as a person who thinks negative thoughts are "reduced" if those negative thoughts overcome positive ones.

## Oxidation Numbers

An oxidation number (sometimes called an oxidation state) is a whole-number integer assigned to each atom in an oxidation-reduction reaction. This makes it easier to keep track of the electrons involved, and to observe the ways in which they change positions. Here are some rules for determining oxidation number.

- 1. The oxidation number for an atom of an element not combined with other elements in a compound is always zero.
- 2. For an ion of any element, the oxidation number is the same as its charge. Thus a sodium ion, which has a charge of +1 and is designated symbolically as $Na^+$, has an oxidation number of +1.
- 3. Certain elements or families form ions in predictable ways:
- a. Alkali metals, such as sodium, always form a +1 ion; oxidation number = +1.
- b. Alkaline earth metals, such as magnesium, always form a +2 ion; oxidation number = +2.
- c. Halogens, such as fluorine, form –1 ions; oxidation number = –1.
- d. Other elements have predictable ways to form ions; but some, such as nitrogen, can have numerous oxidation numbers.
- 4. The oxidation number for oxygen is –2 for most compounds involving covalent bonds.
- 5. When hydrogen is involved in covalent bonds with nonmetals, its oxidation number is +1.
- 6. In binary compounds (compounds with two elements), the element having greater electronegativity is assigned a negative oxidation number that is the same as its charge




Batteries use oxidation-reduction reactions to produce electrical current. *(Lester V. Bergman/ Corbis. Reproduced by permission.)*

when it appears as an anion in ionic compounds.

- 7. When a compound is electrically neutral, the sum of its elements' oxidation states is zero.
- 8. In an ionic chemical species, the sum of the oxidation states for its constituent elements must equal the overall charge.

These rules will not be discussed here; rather, they are presented to show some of the complexities involved in analyzing an oxidation-reduction reaction from a structural standpoint—that is, in terms of the atomic or molecular reactions. For the most part, we will be observing oxidation-reductions phenomenologically, or in terms of their outward effects. A good chemistry textbook should provide a more detailed review of these rules, along with a table showing oxidation numbers of elements and binary compounds.

Oxidation-reduction reactions are easier to understand if they are studied as though they were two half-reactions. Half the reaction involves what happens to the substances and electrons in the oxidizing portion, while the other half-reaction indicates the activities of substances and electrons in the reduction portion.

## REAL-LIFE APPLICATIONS

### Combustion and Explosions

As with any type of chemical reaction, combustion takes place when chemical bonds are broken and new bonds are formed. It so happens that combustion is a particularly dramatic type of oxidation-reduction reaction: whereas we cannot watch iron rust, combustion is a noticeable event. Even more dramatic is combustion that takes place at a rate so rapid that it results in an explosion.

Coal is almost pure carbon, and its combustion in air is a textbook example of oxidation-reduction. Although there is far more nitrogen than oxygen in air (which is a mixture rather than a compound), nitrogen is very unreactive at low temperatures. For this reason, it can be used to clean empty fuel tanks, a situation in which the presence of pure oxygen is extremely dangerous. In any case, when a substance burns, it is reacting with the oxygen in air.

As one might expect from what has already been said about oxidation-reduction, the oxygen is reduced while the carbon is oxidized. In terms of oxidation numbers, the oxidation number of



Oxidation-reduction reactions fuel the space-shuttle at take-off. *(Corbis. Reproduced by permission.)*

carbon jumps from 0 to 4, while that of oxygen is reduced to –2. As they burn, these two form carbon dioxide or $CO_2$, in which the two –2 charges of the oxygen atoms cancel out the +4 charge of the carbon atom to yield a compound that is electrically neutral.

**COMBUSTION IN HUMAN EXPERIENCE.** Combustion has been a significant part of human life ever since our prehistoric ancestors learned how to harness the power of fire to cook food and light their caves. We tend to think of premodern times—to use the memorable title of a book by American historian William Manchester, about the Middle Ages—as *A World Lit Only By Fire.* In fact, our modern age is even more combustion-driven than that of our forebears.

For centuries, burning animal fat—in torches, lamps, and eventually in candles—provided light for humans. Wood fires supplied warmth, as well as a means to cook meals. These were the main uses of combustion, aside from the occasional use of fire in warfare or for other purposes (including that ghastly medieval form of execution, burning at the stake). One notable military application, incidentally, was "Greek fire," created by the Byzantines in the seventh century A.D. A mixture of petroleum, potassium nitrate, and possibly quicklime, Greek fire could burn on water, and was used in naval battles to destroy enemy ships.

For the most part, however, the range of activities to which combustion could be applied was fairly narrow until the development of the steam engine in the period from the late seventeenth century to the early nineteenth century. The steam engine applied the combustion of coal to the production of heat for boiling water, which in turn provided the power to run machinery. By the beginning of the twentieth century, combustion had found a new application in the internal combustion engine, used to power automobiles.

**EXPLOSIONS AND EXPLOSIVES.** An internal combustion engine does not simply burn fuel; rather, by the combined action of the fuel injectors (in a modern vehicle), in concert with the pistons, cylinders, and spark plugs, it actually produces small explosions in the molecules of gasoline. These produce the output of power necessary to turn the crankshaft, and ultimately the wheels.

An explosion, in simple terms, is a sped-up form of combustion. The first explosives were invented by the Chinese during the Middle Ages, and these included not only fireworks and explosive rockets, but gunpowder. Ironically, however, China rejected the use of gunpowder in warfare for many centuries, while Europeans took to it with enthusiasm. Needless to say, Europeans' possession of firearms aided their conquest of the Americas, as well as much of Africa, Asia, and the Pacific, during the period from about 1500 to 1900.

The late nineteenth and early twentieth centuries saw the development of new explosives, such as TNT or trinitrotoluene, a hydrocarbon. Then in the mid-twentieth century came the most fearsome explosive of all: the nuclear bomb. A nuclear explosion is not itself the result of an oxidation-reduction reaction, but of something much more complex—either the splitting of atoms (fission) or the forcing together of atomic nuclei (fusion).

Nuclear bombs release far more energy than any ordinary explosive, but the resulting blast also causes plenty of ordinary combustion. When the United States dropped atomic bombs on the



If not polished regularly, silver responds to oxidation by tarnishing—forming a surface of silver sulfide, or $Ag_2S$. *(Mimmo Jodice/Corbis. Reproduced by permission.)*

Japanese cities of Hiroshima and Nagasaki in August 1945, those cities suffered not only the effects of the immediate blast, but also massive fires resulting from the explosion itself.

**FUELING THE SPACE SHUTTLE.** Oxidation-reduction reactions also fuel the most advanced form of transportation known today, the space shuttle. The actual orbiter vehicle is relatively small compared to its external power apparatus, which consists of two solid rocket boosters on either side, along with an external fuel tank.

Inside the solid rocket boosters are ammonium perchlorate ($NH_4ClO_4$) and powdered aluminum, which undergo an oxidation-reduction reaction that gives the shuttle enormous amounts of extra thrust. As for the larger single external fuel tank, this contains the gases that power the rocket: hydrogen and oxygen.

Because these two are extremely explosive, they must be kept in separate compartments.

When they react, they form water, of course, but in doing so, they also release vast quantities of energy. The chemical equation for this is: $2H_2 + O_2 \rightarrow 2H_2O$ + energy.

On January 28, 1986, something went terribly wrong with this arrangement on the space shuttle *Challenger.* Cold weather had fatigued the O-rings that sealed the hydrogen and oxygen compartments, and the gases fed straight into the flames behind the shuttle itself. This produced a powerful and uncontrolled oxidation-reduction reaction, an explosion that took the lives of all seven astronauts aboard the shuttle.

## The Environment and Human Health

Combustion, though it can do much good, can also do much harm. This goes beyond the obvious: by burning fossil fuels or hydrocarbons, excess carbon (in the form of carbon dioxide and carbon monoxide) is released to the atmosphere, with a damaging effect on the environment.

In fact, oxidation-reduction reactions are intimately connected with the functioning of the natural environment. For example, photosynthesis, the conversion of light to chemical energy by plants, is a form of oxidation-reduction reaction that produces two essentials of human life: oxygen and carbohydrates. Likewise cellular respiration, which along with photosynthesis is discussed in the Carbon essay, is an oxidation-reduction reaction in which living things break down molecules of food to produce energy, carbon dioxide, and water.

Enzymes in the human body regulate oxidation-reduction reactions. These complex proteins, of which several hundred are known, act as catalysts, speeding up chemical processes in the body. Oxidation-reduction reactions also take place in the metabolism of food for energy, with substances in the food broken down into components the body can use.

**OXIDATION: SPOILING AND AGING.** At the same time, oxidation-reduction reactions are responsible for the spoiling of food, the culprit here being the oxidation portion of the reaction. To prevent spoilage, manufacturers of food items often add preservatives, which act as reducing agents.

Oxidation may also be linked with the effects of aging in humans, as well as with other conditions such as cancer, hardening of the arteries, and rheumatoid arthritis. It appears that oxygen molecules and other oxidizing agents, always hungry for electrons, extract these from the membranes in human cells. Over time, this can cause a gradual breakdown in the body's immune system.

To forestall the effects of oxidation, some doctors and scientists recommend antioxidants—natural reducing agents such as vitamin C and vitamin E. The vitamin C in lemon juice can be used to prevent oxidizing on the cut surface of an apple, to keep it from turning brown. Perhaps, some experts maintain, natural reducing agents can also slow the pace of oxidation in the human body.

## Forming a New Surface on Metal

Clearly, oxidization can have a corrosive effect, and nowhere is this more obvious than in the corrosion of metals by exposure to oxidizing agents—primarily oxygen itself. Most metals react with $O_2$, and might corrode so quickly that they become useless, were it not for the formation of a protective coating—an oxide.

Iron forms an oxide, commonly known as rust, but this in fact does little to protect it from corrosion, because the oxide tends to flake off, exposing fresh surfaces to further oxidation. Every year, businesses and governments devote millions of dollars to protecting iron and steel from oxidation by means of painting and other measures, such as galvanizing with zinc. In fact, oxidation-reduction reactions virtually define the world of iron. Found naturally only in ores, the element is purified by heating the ore with coke (impure carbon) in the presence of oxygen, such that the coke reduces the iron.

**COINAGE METALS.** Copper, as we have seen, responds to oxidation by corroding in a different way: not by rusting, but by changing color. A similar effect occurs in silver, which tarnishes, forming a surface of silver sulfide, or $Ag_2S$. Copper and silver are two of the "coinage metals," so named because they have often been used to mint coins. They have been used for this purpose not only because of their beauty, but also due to their relative resistance to corrosion. This resistance has, in fact, earned them the nickname "noble metals."

## KEY TERMS

**ANION:** An ion with a negative charge; pronounced "AN-ie-un."

**BINARY COMPOUND:** A compound involving two elements.

**CHEMICAL REACTION:** A process whereby the chemical properties of a substance are changed by a rearrangement of the atoms in the substance.

**CHEMICAL SPECIES:** A generic term used for any substance studied in chemistry—whether it be an element, compound, mixture, atom, molecule, ion, and so forth.

**COVALENT BONDING:** A type of chemical bonding in which two atoms share valence electrons.

**ELECTROCHEMISTRY:** The study of the relationship between chemical and electrical energy.

**ELECTROLYSIS:** The use of an electric current to produce a chemical change.

**ELECTRONEGATIVITY:** The relative ability of an atom to attract valence electrons.

**CATION:** An ion with a positive charge; pronounced "KAT-ie-un."

**ION:** An atom or group of atoms that has acquired an electric charge due to the loss or gain of electrons.

**OXIDATION:** A chemical reaction in which a substance loses electrons. It is always accompanied by reduction; hence the term oxidation-reduction reaction.

**OXIDATION NUMBER:** A number assigned to each atom in an oxidation-reduction reaction as a means of keeping track of the electrons involved. Another term for oxidation number is "oxidation state."

**OXIDATION-REDUCTION REACTION:** A chemical reaction involving the transfer of electrons.

**REDOX REACTION:** Another name for an oxidation-reduction reaction.

**REDUCTION:** A chemical reaction in which a substance gains electrons. It is always accompanied by oxidation; hence the term oxidation-reduction reaction.

**VALENCE ELECTRONS:** Electrons that occupy the highest energy levels in an atom. These are the only electrons involved in chemical bonding.

The third member of this mini-family is gold, which is virtually noncorrosive. Wonderful as gold is in this respect, however, no one is likely to use it as a roofing material, or for any such large-scale application involving its resistance to oxidation. Aside from the obvious expense, gold is soft, and not very good for structural uses, even if it were much cheaper. Yet there is such a "wonder metal": one that experiences virtually no corrosion, is cheap, and strong enough in alloys to be used for structural purposes. Its name is aluminum.

**ALUMINUM.** There was a time, in fact, when aluminum was even more expensive than gold. When the French emperor Napoleon III wanted to impress a dinner guest, he arranged for the person to be served with aluminum utensils, while less distinguished personages had to settle for "ordinary" gold and silver.

In 1855, aluminum sold for $100,000 a pound, whereas in 1990, the going rate was about $0.74. Demand did not go down—in fact, it increased exponentially—but rather, supply increased, thanks to the development of an inex-

pensive aluminum-reduction process. Two men, one American and one French, discovered this process at the same time: interestingly, their years of birth and death were the same.

Aluminum was once a precious metal because it proved extremely difficult to separate from oxygen. The Hall-Heroult process overcame the problem by applying electrolysis—the use of an electric current to produce a chemical change—as a way of reducing $Al^{3+}$ ions (which have a high affinity for oxygen) to neutral aluminum atoms. In the United States today, 4.5% of the total electricity output is used for the production of aluminum through electrolysis.

The foregoing statistic is staggering, considering just how much electricity Americans use, and it indicates the importance of this once-precious metal. Actually, aluminum oxidizes just like any other metal—and does so quite quickly, as a matter of fact, by forming a coating of aluminum oxide ($Al_2O_3$). But unlike rust, the aluminum oxide is invisible, and acts as a protective coating. Chromium, nickel, and tin react to oxygen in a similar way, but these are not as inexpensive as aluminum.

## Electrochemistry and Batteries

Electrochemistry is the study of the relationship between chemical and electrical energy. Among its applications is the creation of batteries, which use oxidation-reduction reactions to produce an electric current.

A basic battery can be pictured schematically as two beakers of solution connected by a wire. In one solution is the oxidizing agent; in the other, a reducing agent. The wire allows electrons to pass back and forth between the two solutions, but to ensure that the flow goes both ways, the two solutions are also connected by a "salt bridge." The salt bridge contains a gel or solution that permits ions to pass back and forth, but a porous membrane prevents the solutions from actually mixing.

In the lead storage battery of an automobile, lead itself is the reducing agent, while lead (IV) oxide ($PbO_2$) acts as the oxidizing agent. A highly efficient type of battery, able to withstand wide extremes in temperature, the lead storage battery has been in use since 1915. Along the way, features have been altered, but the basic principles have remained—a testament to the soundness of its original design.

The batteries people use for powering all kinds of portable appliances, from flashlights to boom boxes, are called dry cell batteries. In contrast to the model described above, using solutions, a dry cell (as its name implies) involves no liquid components. Instead, it utilizes various elements in a range of combinations, including zinc, magnesium, mercury, silver, nickel, and cadmium. The last two are applied in the nickel-cadmium battery, which is particularly useful because it can be recharged over and over again by an external current. The current turns the products of the chemical reactions in the battery back into reactants.

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# CHEMICAL EQUILIBRIUM

## CONCEPT

Reactions are the "verbs" of chemistry—the activity that chemists study. Many reactions move to their conclusion and then stop, meaning that the reactants have been completely transformed into products, with no means of returning to their original state. In some cases, the reaction truly is irreversible, as for instance when combustion changes both the physical and chemical properties of a substance. There are plenty of other circumstances, however, in which a reverse reaction is not only possible but an ongoing process, as the products of the first reaction become the reactants in a second one. This dynamic state, in which the concentrations of reactants and products remains constant, is referred to as equilibrium. It is possible to predict the behavior of substances in equilibrium through the use of certain laws, which are applied in industries seeking to lower the costs of producing specific chemicals. Equilibrium is also useful in understanding processes that preserve—or potentially threaten—human health.

## HOW IT WORKS

### Chemical Reactions in Brief

What follows is a highly condensed discussion of chemical reactions, and particularly the methods for writing equations to describe them. For a more detailed explanation of these principles, the reader is encouraged to consult the Chemical Reactions essay.

A chemical reaction is a process whereby the chemical properties of a substance are altered by a rearrangement of the atoms in the substance. The changes produced by a chemical reaction are fundamentally different from physical changes, such as boiling or melting liquid water, changes that alter the physical properties of water without affecting its molecular structure.

**INDICATIONS THAT A CHEMICAL REACTION HAS OCCURRED.** Though chemical reactions are most effectively analyzed in terms of molecular properties and behaviors, there are numerous indicators that suggest to us when a chemical reaction has occurred. It is unlikely that all of these will result from any one reaction, and in fact chances are that a particular reaction will manifest only one or two of these effects. Nonetheless, these offer us hints that a reaction has taken place:

Signs that a substance has undergone a chemical reaction:

- Water is produced
- A solid forms
- Gases are produced
- Bubbles are formed
- There is a change in color
- The temperature changes
- The taste of a consumable substance changes
- The smell changes

**CHEMICAL CHANGES CONTRASTED WITH PHYSICAL CHANGES OF TEMPERATURE.** Many of these effects can be produced simply by changing the temperature of a substance, but again, the mere act of applying heat from outside (or removing heat from the substance itself) does not constitute a chemical change. Water can be "produced" by melting ice, but the water was already there—it only changed form. By contrast, when an acid



Many mountain climbers use pressurized oxygen at very high altitudes to maintain proper hemoglobin-oxygen equilibrium. *(Galen Rowell/Corbis. Reproduced by permission.)*

and a base react to form water and a salt, that is a true chemical reaction.

Similarly, the freezing of water forms a solid, but no new substance has been formed; in a chemical reaction, by contrast, two liquids can react to form a solid. When water boils through the application of heat, bubbles form, and a gas or vapor is produced; yet in chemical changes, these effects are not the direct result of applying heat.

In this context, a change in temperature, noted as another sign that a reaction has taken place, is a change of temperature from within the substance itself. Chemical reactions can be classified as heat-producing (exothermic) or heat-absorbing (endothermic). In either case, the transfer of heat is not accomplished simply by creating a temperature differential, as would occur if heat were transferred merely through physical means.

## Why Do Chemical Reactions Occur?

At one time, chemists could only study reactions from "outside," as it were—purely in terms of effects noticeable through the senses. Between the early nineteenth and the early twentieth centuries, however, the entire character of chemistry changed, as did the terms in which chemists discussed reactions. Today, those reactions are analyzed primarily in terms of subatomic, atomic, and molecular properties and activities.

Despite all this progress, however, chemists still do not know exactly what happens in a chemical reaction—but they do have a good approximation. This is the collision model, which explains chemical reactions in terms of collisions between molecules. If the collision is strong enough, it can break the chemical bonds in the reactants, resulting in a re-formation of atoms within different molecules. The more the molecules collide, the more bonds are being broken, and the faster the reaction.

Increase in the numbers of collisions can be produced in two ways: either the concentrations of the reactants are increased, or the temperature is increased. By raising the temperature, the speeds of the molecules themselves increase, and the collisions possess more energy. A certain energy threshold, the activation energy (symbolized $E_a$) must be crossed in order for a reaction to occur. A temperature increase raises the likelihood that a given collision will cross the activation-energy threshold, producing the energy to break the molecular bonds and promote the chemical reaction.

Raising the temperature and the concentrations of reactants can increase the energy and hasten the reactions, but in some cases it is not possible to do either. Fortunately, the rate of reaction can be increased in a third way, through the introduction of a catalyst, a substance that speeds up the reaction without participating in it either as a reactant or product. Catalysts are thus not consumed in the reaction. Many chemistry textbooks discuss catalysts within the context of equilibrium; however, because catalysts play such an important role in human life, in this book they are the subject of a separate essay.

## Chemical Equations Involving Equilibrium

A chemical equation, like a mathematical equation, symbolizes an interaction between entities that produces a particular result. In the case of a chemical equation, the entities are not numbers but reactants, and they interact with each other not through addition or multiplication, but by

chemical reaction. Yet just as a product is the result of multiplication in mathematics, a product in a chemical equation is the substance or substances that result from the reaction.

Instead of an equals sign between the reactants and the product, an arrow is used. When the arrow points to the right, this indicates a forward reaction; conversely, an arrow pointing to the left symbolizes a reverse reaction. In a reverse reaction, the products of a forward reaction have become the reactants, and the reactants of the forward reaction are now the products. This is indicated by an arrow that points toward the left.

Chemical equilibrium, which occurs when the ratio between the reactants and products is constant, and in which the forward and reverse reactions take place at the same rate, is symbolized thus: ⇌. Note that the arrows, the upper one pointing right and the lower one pointing left, are of the same length. There may be certain cases, discussed below, in which it is necessary to show these arrows as unequal in length as a means of indicating the dominance of either the forward or reverse reaction.

Chemical equations usually include notation indicating the state or phase of matter for the reactants and products: *(s)* for a solid; *(l)* for a liquid; *(g)* for a gas. A fourth symbol, *(aq)*, indicates a substance dissolved in water—that is, an aqueous solution. In the following paragraphs, we will apply a chemical equation to the demonstration of equilibrium, but will not discuss the balancing of equations. The reader is encouraged to consult the passage in the Chemical Reactions essay that addresses that process, vital to the recording of accurate data.

**A SIMPLE EQUILIBRIUM EQUATION.** Let us now consider a simple equation, involving the reaction between water and carbon monoxide (CO) at high temperatures in a closed container. The initial equation is written thus: $H_2O(g) + CO(g) \rightarrow H_2(g) + CO_2g)$. In plain English, water in the gas phase (steam) has reacted with carbon monoxide to produce hydrogen gas and carbon dioxide.

As the reaction proceeds, the amount of reactants decreases, and the concentration of products increases. At some point, however, there will be a balance between the numbers of products and reactants—a state of chemical equilibrium represented by changing the right-pointing arrow to an equilibrium symbol: $H_2O(g) + CO(g) \leftrightharpoons H_2(g) + CO_2g)$. Assuming that the system is not disturbed (that is, that the container is kept closed and no outside substances are introduced), equilibrium will continue to be maintained, because the reverse reaction is occurring at the same rate as the forward one.

Note what has been said here: reactions are still occurring, but the forward and rearward reactions balance one another. Thus equilibrium is not a static condition, but a dynamic one, and indeed, chemical equilibrium is sometimes referred to as "dynamic equilibrium." On the other hand, some chemists refer to chemical equilibrium simply as equilibrium, but here the qualifier chemical has been used to distinguish this from the type of equilibrium studied in physics. Physical equilibrium, which involves factors such as center of gravity, does help us to understand chemical equilibrium, but it is a different phenomenon.

## REAL-LIFE APPLICATIONS

### Homogeneous and Heterogeneous Equilibria

It should be noted that the equation used above identifies a situation of homogeneous equilibrium, in which all the substances are in the same phase or state of matter—gas, in this case. It is also possible to achieve chemical equilibrium in a reaction involving substances in more than one phase of matter.

An example of such heterogeneous equilibrium is the decomposition of calcium carbonate for the production of lime, a process that involves the application of heat. Here the equation would be written thus: $CaCO_3(s) \leftrightharpoons CaO(s) + CO_2(g)$. Both the calcium carbonate ($CaCO_3$) and the lime (CaO) are solids, whereas the carbon dioxide produced in this reaction is a gas.

### The Equilibrium Constant

In 1863, Norwegian chemists Cato Maximilian Guldberg (1836-1902) and Peter Waage (1833-1900)—who happened to be brothers-in-law—formulated what they called the law of mass action. Today, this is called the law of chemical equilibrium, which states that the direction taken by a reaction is dependant not merely on the mass of the various components of the reaction,

but also upon the concentration—that is, the mass present in a given volume.

This can be expressed by the formula $aA + bB \rightleftharpoons cC + dD$, where the capital letters represent chemical species, and the italicized lowercase letters indicate their coefficients. The equation $[C]^c[D]^d/[A]^a[B]^b$ yields what is called an equilibrium constant, symbolized *K*.

The above formula expresses the equilibrium constant in terms of molarity, the amount of solute in a given volume of solution, but in the case of gaseous reactants and products, the equilibrium constant can also be expressed in terms of partial pressures. In the reaction of water and carbon monoxide to produce hydrogen molecules and carbon dioxide ($H_2O + CO \leftrightharpoons H_2 + CO_2$). In chemical reactions involving solids, however, the concentration of the solid—because it is considered to be invariant—does not appear in the equilibrium constant. In the reaction described earlier, in which calcium carbonate was in equilibrium with solid lime and gaseous carbon dioxide, $K$ = pressure of $CO_2$.

We will not attempt here to explore the equilibrium constant in any depth, but it is important to recognize its usefulness. For a particular reaction at a specific temperature, the ratio of concentrations between reactants and products will always have the same value—the equilibrium constant, or *K*. Because it is not dependant on the amounts of reactants and products mixed together initially, *K* remains the same: the concentrations themselves may vary, but the ratios between the concentrations in a given situation do not.

## Le Châtelier's Principle

Not all situations of equilibrium are alike: depending on certain factors, the position of equilibrium may favor one side of the equation or the other. If a company is producing chemicals for sale, for example, its production managers will attempt to influence reactions in such a way as to favor the forward reaction. In such a situation, it is said that the equilibrium position has been shifted to the right. In terms of physical equilibrium, mentioned above, this would be analogous to what would happen if you were holding your arms out on either side of your body, with a heavy lead weight in your left hand and a much smaller weight in the right hand. Your center of gravity, or equilibrium position, would shift to the left to account for the greater force exerted by the heavier weight.

A value of *K* significantly above 1 causes a shift to the right, meaning that at equilibrium, there will be more products than reactants. This is a situation favorable to a chemical company's managers, who desire to create more of the product from less of the reactants. However, nature abhors an imbalance, as expressed in Le Châtelier's principle. Named after French chemist Henri Le Châtelier (1850-1936), this principle maintains that whenever a stress or change is imposed on a chemical system in equilibrium, the system will adjust the amounts of the various substances to reduce the impact of that stress.

Suppose we add more of a particular substance to increase the rate of the forward reaction. In an equation for this reaction, the equilibrium symbol is altered, with a longer arrow pointing to the right to indicate that the forward reaction is favored. Again, the equilibrium position has shifted to the right—just as one makes physical adjustments to account for an imbalanced weight. The system responds by working to consume more of the reactant, thus adjusting to the stress that was placed on it by the addition of more of that substance. By the same token, if we were to remove a particular reactant or product, the system would shift in the direction of the detached component.

Note that Le Châtelier's principle is mathematically related to the equilibrium constant. Suppose we have a basic equilibrium equation of $A + B \rightleftharpoons C$, with A and B each having molarities of 1, and C a molarity of 4. This tells us that *K* is equal to the molarity of C divided by that of A multiplied by B = $4/(1 \cdot 1)$. Suppose, now, that enough of C were added to bring its concentration up to 6. This would mean that the system was no longer at equilibrium, because $C/(A \cdot B)$ no longer equals 4. In order to return the ratio to 4, the numerator (C) must be decreased, while the denominator ($A \cdot B$) is increased. The reaction thus shifts from right to left.

**Changes in volume and temperature.** If the volume of gases in a closed container is decreased, the pressure increases. An equilibrium system will therefore shift in the direction that reduces the pressure; but if the volume is increased, thus reducing the pressure, the system will respond by shifting to

increase pressure. Note, however, that not all increases in pressure lead to a shift in the equilibrium. If the pressure were increased by the addition of a noble gas, the gas itself—since these elements are noted for their lack of reactivity—would not be part of the reaction. Thus the species added would not be part of the equilibrium constant expression, and there would be no change in the equilibrium.

In any case, no change in volume alters the equilibrium constant *K*; but where changes in temperature are involved, *K* is indeed altered. In an exothermic, or heat-producing reaction, the heat is treated as a product. Thus, when nitrogen and hydrogen react, they produce not only ammonia, but a certain quantity of heat. If this system is at equilibrium, Le Châtelier's principle shows that the addition of heat will induce a shift in equilibrium to the left—in the direction that consumes heat or energy.

The reverse is true in an endothermic, or heat-absorbing reaction. As in the process described earlier, the thermal decomposition of calcium carbonate produces lime and carbon dioxide. Because heat is used to cause this reaction, the amount of heat applied is treated as a reactant, and an increase in temperature will cause the equilibrium position to shift to the right.

## Equilibrium and Health

Discussions of chemical equilibrium tend to be rather abstract, as the foregoing sections on the equilibrium constant and Le Châtelier's principle illustrate. (The reader is encouraged to consult additional sources on these topics, which involve a number of particulars that have been touched upon only briefly here.) Despite the challenges involved in addressing the subject of equilibrium, the results of chemical equilibrium can be seen in processes involving human health.

The cooling of food with refrigerators, along with means of food preservation that do not involve changes in temperature, maintains chemical equilibrium in the foods and thereby prevents or at least retards spoilage. Even more important is the maintenance of equilibrium in reactions between hemoglobin and oxygen in human blood.

**HEMOGLOBIN AND OXYGEN.** Hemoglobin, a protein containing iron, is the material in red blood cells responsible for transporting oxygen to the cells. Each hemoglobin molecule attaches to four oxygen atoms, and the equilibrium conditions of the hemoglobin-oxygen interaction can be expressed thus: $Hb(aq) + 4O_2(g) \leftrightharpoons Hb(O_2)_4(aq)$, where "Hb" stands for hemoglobin. As long as there is sufficient oxygen in the air, a healthy equilibrium is maintained; but at high altitudes, considerable changes occur.

At significant elevations above sea level, the air pressure is lowered, and thus it is more difficult to obtain the oxygen one needs. The result, in accordance with Le Châtelier's principle, is a shift in equilibrium to the left, away from the oxygenated hemoglobin. Without adequate oxygen fed to the body's cells and tissues, a person tends to feel light-headed.

When someone not physically prepared for the change is exposed to high altitudes, it may be necessary to introduce pressurized oxygen from an oxygen tank. This shifts the equilibrium to the right. For people born and raised at high altitudes, however, the body's chemistry performs the equilibrium shift—by producing more hemoglobin, which also shifts equilibrium to the right.

**HEMOGLOBIN AND CARBON MONOXIDE.** When someone is exposed to carbon monoxide gas, a frightening variation on the normal hemoglobin-oxygen interaction occurs. Carbon monoxide "fools" hemoglobin into mistaking it for oxygen because it also bonds to hemoglobin in groups of four, and the equilibrium expression thus becomes: $Hb(aq) + 4CO(g) \leftrightharpoons Hb(CO)_4(aq)$. Instead of hemoglobin, what has been produced is called carboxyhemoglobin, which is even redder than hemoglobin. Therefore, one sign of carbon monoxide poisoning is a flushed face.

The bonds between carbon monoxide and hemoglobin are about 300 times as strong as those between hemoglobin and oxygen, and this means a shift in equilibrium toward the right side of the equation—the carboxyhemoglobin side. It also means that *K* for the hemoglobin-carbon monoxide reaction is much higher than for the hemoglobin-oxygen reaction. Due to the affinity of hemoglobin for carbon monoxide, the hemoglobin puts a priority on carbon monoxide bonds, and hemoglobin that has bonded with carbon monoxide is no longer available to carry oxygen.

## KEY TERMS

**ACTIVATION ENERGY:** The minimal energy required to convert reactants into products, symbolized $E_a$.

**AQUEOUS SOLUTION:** A mixture of water and a substance that is dissolved in it.

**CATALYST:** A substance that speeds up a chemical reaction without participating in it, either as a reactant or product. Catalysts are thus not consumed in the reaction.

**CHEMICAL EQUATION:** A representation of a chemical reaction in which the chemical symbols on the left stand for the reactants, and those on the right are the product or products.

**CHEMICAL EQUILIBRIUM:** A situation in which the ratio between the reactants and products in a chemical reaction is constant, and in which the forward reactions and reverse reactions take place at the same rate.

**CHEMICAL REACTION:** A process whereby the chemical properties of a substance are changed by a rearrangement of the atoms in the substance.

**CHEMICAL SPECIES:** A generic term used for any substance studied in chemistry—whether it be an element, compound, mixture, atom, molecule, ion, and so forth.

**COEFFICIENT:** a number used to indicate the presence of more than one unit—typically, more than one molecule—of a chemical species in a chemical equation.

**COLLISION MODEL:** The theory that chemical reactions are the result of collisions between molecules that are strong enough to break bonds in the reactants, resulting in a reformation of atoms.

**ENDOTHERMIC:** A term describing a chemical reaction in which heat is absorbed or consumed.

Carbon monoxide in small quantities can cause headaches and dizziness, but larger concentrations can be fatal. To reverse the effects of the carbon monoxide, pure oxygen must be introduced to the body. It will react with the carboxyhemoglobin to produce properly oxygenated hemoglobin, along with carbon monoxide: $Hb(CO)_4(aq) + 4O_2(g) \leftrightharpoons Hb(O_2)_4(aq) + 4CO(g)$. The gaseous carbon monoxide thus produced is dissipated when the person exhales.

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## KEY TERMS CONTINUED

**EXOTHERMIC:** A term describing a chemical reaction in which heat is produced.

**FORWARD REACTION:** A chemical reaction symbolized by a chemical equation in which the reactants and product are separated by an arrow that points to the right, toward the products.

**HETEROGENEOUS EQUILIBRIUM:** Chemical equilibrium in which the substances involved are in different phases of matter (solid, liquid, gas.)

**HOMOGENEOUS EQUILIBRIUM:** Chemical equilibrium in which the substances involved are in the same phase of matter.

**LE CHÂTELIER'S PRINCIPLE:** A statement, formulated by French chemist Henri Le Châtelier (1850-1936), which holds that whenever a stress or change is imposed on a system in chemical equilibrium, the system will adjust the amounts of the various substances in such a way as to reduce the impact of that stress.

**PRODUCT:** The substance or substances that result from a chemical reaction.

**REACTANT:** A substance that interacts with another substance in a chemical reaction, resulting in a product.

**REVERSE REACTION:** A chemical reaction symbolized by a chemical equation in which the products of a forward reaction have become the reactants, and the reactants of the forward reaction are now the products. This is indicated by an arrow that points toward the left.

**SYSTEM:** In chemistry and other sciences, the term "system" usually refers to any set of interactions isolated from the rest of the universe. Anything outside of the system, including all factors and forces irrelevant to a discussion of that system, is known as the environment.

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# CATALYSTS

## CONCEPT

In most of the processes studied within the physical sciences, the lesson again and again is that nature provides no "free lunch"; in other words, it is not possible to get something for nothing. A chemical reaction, for instance, involves the creation of substances different from those that reacted in the first place, but the number of atoms involved does not change. In view of nature's inherently conservative tendencies, then, the idea of a catalyst—a substance that speeds up a reaction without being consumed—seems almost like a magic trick. But catalysts are very real, and their presence in the human body helps to sustain life. Similarly, catalysts enable the synthesis of foods, and catalytic converters in automobiles protect the environment from dangerous exhaust fumes. Yet the presence of one particular catalyst in the upper atmosphere poses such a threat to Earth's ozone layer that production of certain chemicals containing that substance has been banned.

## HOW IT WORKS

### Reactions and Collisions

In a chemical reaction, substances known as reactants interact with one another to create new substances, called products. In the present context, our concern is not with the reactants and products themselves, but with an additional entity, an agent that enables the reaction to move forward at faster rates and lower temperatures.

According to the collision model generally accepted by chemists, chemical reactions are the result of collisions between molecules. Collisions that are sufficiently energetic break the chemical bonds that hold molecules together; as a result, the atoms in those molecules are free to recombine with other atoms to form new molecules. Hastening of a chemical reaction can be produced in one of three ways. If the concentrations of the reactants are increased, this means that more molecules are colliding, and potentially more bonds are being broken. Likewise if the temperature is increased, the speeds of the molecules themselves increase, and their collisions possess more energy.

Energy is an important component in the chemical reaction because a certain threshold, called the activation energy ($E_a$), must be crossed before a reaction can occur. A temperature increase raises the energy of the collisions, increasing the likelihood that the activation-energy threshold will be crossed, resulting in the breaking of molecular bonds.

### Catalysts and Catalysis

It is not always feasible or desirable, however, to increase the concentration of reactants, or the temperature of the system in which the reaction is to occur. Many of the processes that take place in the human body, for instance, "should" require high temperatures—temperatures too high to sustain human life. But fortunately, our bodies contain proteins called enzymes, discussed later in this essay, that facilitate the necessary reactions without raising temperatures or increasing the concentrations of substances.

An enzyme is an example of a catalyst, a substance that speeds up a reaction without participating in it either as a reactant or product. Catalysts are thus not consumed in the reaction. The



Catalytic converters employ a catalyst to facilitate the transformation of pollution-causing exhausts to less harmful substances. *(Ian Harwood; Ecoscene/Corbis. Reproduced by permission.)*

catalyst does its work—catalysis—by creating a different path for the reaction, and though the means whereby it does this are too complex to discuss in detail here, the process of catalyst can at least be presented in general terms.

Imagine a graph whose x-axis is labeled "reaction progress," while the y-axis bears the legend "energy." There is some value of y equal to the normal activation energy, and in the course of experiencing the molecular collisions that lead to a reaction, the reactants reach this level. In a catalyzed reaction, however, the level of activation energy necessary for the reaction is represented by a lower y-value on the graph. The catalyzed substances do not need to have as much energy as they do without a catalyst, and therefore the reaction can proceed more quickly—without changing the temperature or concentrations of reactants.

## Real-Life Applications

### A Brief History of Catalysis

Long before chemists recognized the existence of catalysts, ordinary people had been using the process of catalysis for a number of purposes: making soap, for instance, or fermenting wine to create vinegar, or leavening bread. Early in the nineteenth century, chemists began to take note of this phenomenon.



Fritz Haber. *(Austrian Archives/Corbis. Reproduced by permission.)*

In 1812, Russian chemist Gottlieb Kirchhof was studying the conversion of starches to sugar in the presence of strong acids when he noticed something interesting. When a suspension of starch in water was boiled, Kirchhof observed, no change occurred in the starch. However, when he added a few drops of concentrated acid before boiling the suspension (that is, particles of starch suspended in water), he obtained a very different result. This time, the starch broke down to form glucose, a simple sugar, while the acid—which clearly had facilitated the reaction—underwent no change.

Around the same time, English chemist Sir Humphry Davy (1778-1829) noticed that in certain organic reactions, platinum acted to speed along the reaction without undergoing any change. Later on, Davy's star pupil, the great British physicist and chemist Michael Faraday (1791-1867), demonstrated the ability of platinum to recombine hydrogen and oxygen that had been separated by the electrolysis of water. The catalytic properties of platinum later found application in catalytic converters, as we shall see.

**AN IMPROVED DEFINITION.** In 1835, Swedish chemist Jons Berzelius (1779-1848) provided a name to the process Kirchhof and Davy had observed from very different perspectives: catalysis, derived from the Greek words *kata* ("down") and *lyein* ("loosen.") As Berzelius defined it, catalysis involved an activity quite different from that of an ordinary chemical reaction. Catalysis induced decomposition in substances, resulting in the formation of new compounds—but without the catalyst itself actually entering the compound.

Berzelius's definition assumed that a catalyst manages to do what it does without changing at all. This was perfectly adequate for describing heterogeneous catalysis, in which the catalyst and the reactants are in different phases of matter. In the platinum-catalyzed reactions that Davy and Faraday observed, for instance, the platinum is a solid, while the reaction itself takes place in a gaseous or liquid state. However, homogeneous catalysis, in which catalyst and reactants are in the same state, required a different explanation, which English chemist Alexander William Williamson (1824-1904) provided in an 1852 study.

In discussing the reaction observed by Kirchhof, of liquid sulfuric acid with starch in an aqueous solution, Williamson was able to show that the catalyst does break down in the course of the reaction. As the reaction takes place, it forms an intermediate compound, but this too is broken down before the reaction ends. The catalyst thus emerges in the same form it had at the beginning of the reaction.

## Enzymes: Helpful Catalysts in the Body

In 1833, French physiologist Anselme Payen (1795-1871) isolated a material from malt that accelerated the conversion of starch to sugar, as for instance in the brewing of beer. Payen gave the name "diastase" to this substance, and in 1857, the renowned French chemist Louis Pasteur (1822-1895) suggested that lactic acid fermentation is caused by a living organism.

In fact, the catalysts studied by Pasteur are not themselves separate organisms, as German biochemist Eduard Buchner (1860-1917) showed in 1897. Buchner isolated the catalysts that bring about the fermentation of alcohol from living yeast cells—what Payen had called "diastase," and Pasteur "ferments." Buchner demonstrated that these are actually chemical substances, not organisms. By that time, German physiologist Willy Kahne had suggested the name "enzyme" for these catalysts in living systems.

Enzymes are made up of amino acids, which in turn are constructed from organic compounds called proteins. About 20 amino acids make up the building blocks of the many thousands of known enzymes. The beauty of an enzyme is that it speeds up complex, life-sustaining reactions in the human body—reactions that would be too slow at ordinary body temperatures. Rather than force the body to undergo harmful increases in temperature, the enzyme facilitates the reaction by opening up a different reaction pathway that allows a lower activation energy.

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.

Because numerous interactions are required in their work of catalysis, enzymes are very large, and may have atomic mass figures as high as 1 million amu. However, it should be noted that reactions are catalyzed at very specific locations—called active sites—on an enzyme. The reactant molecule fits neatly into the active site on the enzyme, much like a key fitting in a lock; hence the name of this theory, the "lock-and-model."

## Catalysis and the Environment

The exhaust from an automobile contains many substances that are harmful to the environment. As a result of increased concerns regarding the potential damage to the atmosphere, the federal government in the 1970s mandated the adoption of catalytic converters, devices that employ a catalyst to transform pollutants in the exhaust to less harmful substances.

Platinum and palladium are favored materials for catalytic converters, though some nonmetallic materials, such as ceramics, have been used as well. In any case, the function of a catalytic converter is to convert exhausts through oxidation-reduction reactions. Nitric oxide is reduced to molecular oxygen and nitrogen; at the same time, the hydrocarbons in petroleum, along with carbon monoxide, are oxidized to form carbon dioxide and water. Sometimes a reducing agent, such as ammonia, is used to make the reduction process more effective.

**A dangerous catalyst in the atmosphere.** Around the same time that automakers began rolling out models equipped with catalytic converters, scientists and the general public alike became increasingly concerned about another threat to the environment. In the upper atmosphere of Earth are traces of ozone, a triatomic (three-atom) molecular form of oxygen which protects the planet from the Sun's ultraviolet rays. During the latter part of the twentieth century, it became apparent that a hole had developed in the ozone layer over Antarctica, and many chemists suspected a culprit in chlorofluorocarbons, or CFCs.

CFCs had long been used in refrigerants and air conditioners, and as propellants in aerosol sprays. Because they were nontoxic and noncorrosive, they worked quite well for such purposes, but the fact that they are chemically unreactive had an extremely negative side-effect. Instead of reacting with other substances to form new compounds, they linger in Earth's atmosphere, eventually drifting to high altitudes, where ultraviolet light decomposes them. The real trouble begins when atoms of chlorine, isolated from the CFC, encounter ozone.

Chlorine acts as a catalyst to transform the ozone to elemental oxygen, which is not nearly as effective as ozone for shielding Earth from ultraviolet light. It does so by interacting also with monatomic, or single-atom oxygen, with which it produces ClO, or the hypochlorite ion. The end result of reactions between chlorine, monatomic oxygen, hypochlorite, and ozone is the production of chlorine, hypochlorite, and diatomic oxygen—in other words, no more ozone. It is estimated that a single chlorine atom can destroy up to 1 million ozone molecules per second.

Due to concerns about the danger to the ozone layer, an international agreement called the Montreal Protocol, signed in 1996, banned the production of CFCs and the coolant Freon that contains them. But people still need coolants for their homes and cars, and this has led to the creation of substitutes—most notably hydrochlorofluorocarbons (HCFCs), organic compounds that do not catalyze ozone.

## Other Examples of Catalysts

Catalysts appear in a number of reactions, both natural and artificial. For instance, catalysts are used in the industrial production of ammonia,

## KEY TERMS

**ACTIVATION ENERGY:** The minimal energy required to convert reactants into products, symbolized $E_a$

**AQUEOUS SOLUTIONS:** A mixture of water and a substance that is dissolved in it.

**CATALYST:** A substance that speeds up a chemical reaction without participating in it, either as a reactant or product. Catalysts are thus not consumed in the reaction.

**CHEMICAL REACTION:** A process whereby the chemical properties of a substance are changed by a rearrangement of the atoms in the substance.

**COLLISION MODEL:** The theory that chemical reactions are the result of collisions between molecules strong enough to break bonds in the reactants, resulting in a reformation of atoms.

**HETEROGENEOUS CATALYSIS:** A reaction in which the catalyst and the reactants are in different phases of matter.

**HOMOGENEOUS CATALYSIS:** A reaction in which catalyst and reactants are in the same phase of matter.

**PRODUCT:** The substance or substances that result from a chemical reaction.

**REACTANT:** A substance that interacts with another substance in a chemical reaction, resulting in a product.

**SYSTEM:** In chemistry and other sciences, the term "system" usually refers to any set of interactions isolated from the rest of the universe. Anything outside of the system, including all factors and forces irrelevant to a discussion of that system, is known as the environment.

nitric acid (produced from ammonia), sulfuric acid, and other substances. The ammonia process, developed in 1908 by German chemist Fritz Haber (1868-1934), is particularly noteworthy. Using iron as a catalyst, Haber was able to combine nitrogen and hydrogen under pressure to form ammonia—one of the world's most widely used chemicals.

Eighteen ninety-seven was a good year for catalysts. In that year, it was accidentally discovered that mercury catalyzes the reaction by which indigo dye is produced; also in 1897, French chemist Paul Sabatier (1854-1941) found that nickel catalyzes the production of edible fats. Thanks to Sabatier's discovery, nickel is used to transform inedible plant oils to margarine and shortening.

Another good year for catalysts—particularly those involved in the production of polymers—was 1953. That was the year when German chemist Karl Ziegler (1898-1973) discovered a resin catalyst for the production of polyethylene, which produced a newer, tougher product with a much higher melting point than polyethylene as it was produced up to that time. Also in 1953, Italian chemist Giulio Natta (1903-1979) adapted Ziegler's idea, and developed a new type of plastic he called "isotactic" polymers. These could be produced easily, and in abundance, through the use of catalysts.

One of the lessons of chemistry, or indeed of any science, is that there are few things chemists can do that nature cannot achieve on a far more wondrous scale. No artificial catalyst can compete with enzymes, and no use of a catalyst in a laboratory can compare with the grandeur of that which takes place on the Sun. As German-American physicist Hans Bethe (1906-) showed in 1938, the reactions of hydrogen that form helium on the surface of the Sun are catalyzed by carbon—the same element, incidentally, found in all living things on Earth.

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# ACIDS AND BASES

## CONCEPT

The name "acid" calls to mind vivid sensory images—of tartness, for instance, if the acid in question is meant for human consumption, as with the citric acid in lemons. On the other hand, the thought of laboratory- and industrial-strength substances with scary-sounding names, such as sulfuric acid or hydrofluoric acid, carries with it other ideas—of acids that are capable of destroying materials, including human flesh. The name "base," by contrast, is not widely known in its chemical sense, and even when the older term of "alkali" is used, the sense-impressions produced by the word tend not to be as vivid as those generated by the thought of "acid." In their industrial applications, bases too can be highly powerful. As with acids, they have many household uses, in substances such as baking soda or oven cleaners. From a taste standpoint, (as anyone who has ever brushed his or her teeth with baking soda knows), bases are bitter rather than sour. How do we know when something is an acid or a base? Acid-base indicators, such as litmus paper and other materials for testing pH, offer a means of judging these qualities in various substances. However, there are larger structural definitions of the two concepts, which evolved in three stages during the late nineteenth and early twentieth centuries, that provide a more solid theoretical underpinning to the understanding of acids and bases.

## HOW IT WORKS

### Introduction to Acids and Bases

Prior to the development of atomic and molecular theory in the nineteenth century, followed by the discovery of subatomic structures in the late nineteenth and early twentieth centuries, chemists could not do much more than make measurements and observations. Their definitions of substances were purely phenomenological—that is, the result of experimentation and the collection of data. From these observations, they could form general rules, but they lacked any means of "seeing" into the atomic and molecular structures of the chemical world.

The phenomenological distinctions between acids and bases, gathered by scientists from ancient times onward, worked well enough for many centuries. The word "acid" comes from the Latin term *acidus,* or "sour," and from an early period, scientists understood that substances such as vinegar and lemon juice shared a common acidic quality. Eventually, the phenomenological definition of acids became relatively sophisticated, encompassing such details as the fact that acids produce characteristic colors in certain vegetable dyes, such as those used in making litmus paper. In addition, chemists realized that acids dissolve some metals, releasing hydrogen in the process.

**WHY "BASE" AND NOT "ALKALI"?** The word "alkali" comes from the Arabic *al-qili,* which refers to the ashes of the seawort plant. The latter, which typically grows in marshy areas, was often burned to produce soda ash, used in making soap. In contrast to acids, bases—caffeine, for example—have a bitter taste, and many of them feel slippery to the touch. They also produce characteristic colors in the vegetable dyes of litmus paper, and can be used to promote certain chemical reactions. Note that today chemists use the word "base" instead of "alkali,"

the reason being that the latter term has a narrower meaning: all alkalies are bases, but not all bases are alkalies.

Originally, "alkali" referred only to the ashes of burned plants, such as seawort, that contained either sodium or potassium, and from which the oxides of sodium and potassium could be obtained. Eventually, alkali came to mean the soluble hydroxides of the alkali and alkaline earth metals. This includes sodium hydroxide, the active ingredient in drain and oven cleaners; magnesium hydroxide, used for instance in milk of magnesia; potassium hydroxide, found in soaps and other substances; and other compounds. Broad as this range of substances is, it fails to encompass the wide array of materials known today as bases—compounds which react with acids to form salts and water.

## Toward a Structural Definition

The reaction to form salts and water is, in fact, one of the ways that acids and bases can be defined. In an aqueous solution, hydrochloric acid and sodium hydroxide react to form sodium chloride—which, though it is suspended in an aqueous solution, is still common table salt—along with water. The equation for this reaction is $HCl(aq) + NaOH(aq) \rightarrow H_2O + NaCl(aq)$. In other words, the sodium (Na) ion in sodium hydroxide switches places with the hydrogen ion in hydrochloric acid, resulting in the creation of NaCl (salt) along with water.

But why does this happen? Useful as this definition regarding the formation of salts and water is, it is still not structural—in other words, it does not delve into the molecular structure and behavior of acids and bases. Credit for the first truly structural definition of the difference goes to the Swedish chemist Svante Arrhenius (1859-1927). It was Arrhenius who, in his doctoral dissertation in 1884, introduced the concept of an ion, an atom possessing an electric charge.

His understanding was particularly impressive in light of the fact that it was 13 more years before the discovery of the electron, the subatomic particle responsible for the creation of ions. Atoms have a neutral charge, but when an electron or electrons depart, the atom becomes a positive ion or cation. Similarly, when an electron or electrons join a previously uncharged atom, the result is a negative ion or anion. Not only did the concept of ions greatly influence the future of chemistry, but it also provided Arrhenius with the key necessary to formulate his distinction between acids and bases.



SVANTE ARRHENIUS. *(Hulton-Deutsch Collection/Corbis. Reproduced by permission.)*

## The Arrhenius Definition

Arrhenius observed that molecules of certain compounds break into charged particles when placed in liquid. This led him to the Arrhenius acid-base theory, which defines an acid as any compound that produces hydrogen ions ($H^+$) when dissolved in water, and a base as any compound that produces hydroxide ions ($OH^-$) when dissolved in water.

This was a good start, but two aspects of Arrhenius's theory suggested the need for a definition that encompassed more substances. First of all, his theory was limited to reactions in aqueous solutions. Though many acid-base reactions do occur when water is the solvent, this is not always the case.

Second, the Arrhenius definition effectively limited acids and bases only to those ionic compounds, such as hydrochloric acid or sodium hydroxide, which produced either hydrogen or



The tartness of lemons and limes is a function of their acidity—specifically the way in which citric acid molecules fit into the tongue's "sweet" receptors. *(Orion Press/Corbis. Reproduced by permission.)*

hydroxide ions. However, ammonia, or $NH_3$, acts like a base in aqueous solutions, even though it does not produce the hydroxide ion. The same is true of other substances, which behave like acids or bases without conforming to the Arrhenius definition.

These shortcomings pointed to the need for a more comprehensive theory, which arrived with the formulation of the Brønsted-Lowry definition by English chemist Thomas Lowry (1874-1936) and Danish chemist J. N. Brønsted (1879-1947). Nonetheless, Arrhenius's theory represented an important first step, and in 1903, he was awarded the Nobel Prize in Chemistry for his work on the dissociation of molecules into ions.

## The Brønsted-Lowry Definition

The Brønsted-Lowry acid-base theory defines an acid as a proton ($H^+$) donor, and a base as a proton acceptor, in a chemical reaction. Protons are represented by the symbol $H^+$, and in representing acids and bases, the symbols HA and $A^-$, respectively, are used. These symbols indicate that an acid has a proton it is ready to give away, while a base, with its negative charge, is ready to receive the positively charged proton.

Though it is used here to represent a proton, it should be pointed out that $H^+$ is also the hydrogen ion—a hydrogen atom that has lost its sole electron and thus acquired a positive charge.

It is thus really nothing more than a lone proton, but this is the one and only case in which an atom and a proton are exactly the same thing. In an acid-base reaction, a molecule of acid is "donating" a proton, in the form of a hydrogen ion. This should not be confused with a far more complex process, nuclear fusion, in which an atom gives up a proton to another atom.

**AN ACID-BASE REACTION IN BRØNSTED-LOWRY THEORY.** The most fundamental type of acid-base reaction in Brønsted-Lowry theory can be symbolized thus $HA(aq) + H_2O(l) \rightarrow H_3O^+(aq) + A^-(aq)$. The first acid shown—which, like three of the four "players" in this equation, is dissolved in an aqueous solution—combines with water, which can serve as either an acid or a base. In the present context, it functions as a base.

Water molecules are polar, meaning that the negative charges tend to congregate on one end of the molecule with the oxygen atom, while the positive charges remain on the other end with the hydrogen atoms. The Brønsted-Lowry model emphasizes the role played by water, which pulls the proton from the acid, resulting in the creation of $H_3O^+$, known as the hydronium ion.

The hydronium ion produced here is an example of a conjugate acid, an acid formed when a base accepts a proton. At the same time, the acid has lost its proton, becoming $A^-$, a conjugate base—that is, the base formed when an acid releases a proton. These two products of the reaction are called a conjugate acid-base pair, a term that refers to two substances related to one another by the donating of a proton.

Brønsted and Lowry's definition represents an improvement over that of Arrhenius, because it includes all Arrhenius acids and bases, as well as other chemical species not encompassed in Arrhenius theory. An example, mentioned earlier, is ammonia. Though it does not produce $OH^-$ ions, ammonia does accept a proton from a water molecule, and the reaction between these two (with water this time serving the function of acid) produces the conjugate acid-base pair of $NH_4^+$ (an ammonium ion) and $OH^-$. Note that the latter, the hydroxide ion, was not produced by ammonia, but is the conjugate base that resulted when the water molecule lost its $H^+$ atom or proton.

## The Lewis Definition

Despite the progress offered to chemists by the Brønsted-Lowry model, it was still limited to describing compounds that contain hydrogen. As American chemist Gilbert N. Lewis (1875-1946) recognized, this did not encompass the full range of acids and bases; what was needed, instead, was a definition that did not involve the presence of a hydrogen atom.

Lewis is particularly noted for his work in the realm of chemical bonding. The bonding of atoms is the result of activity on the part of the valence electrons, or the electrons at the "outside" of the atom. Electrons are arranged in different ways, depending on the type of bonding, but they always bond in pairs.

According to the Lewis acid-base theory, an acid is the reactant that accepts an electron pair from another reactant in a chemical reaction, while a base is the reactant that donates an electron pair to another reactant. As with the Brønsted-Lowry definition, the Lewis definition is reaction-dependant, and does not define a compound as an acid or base in its own right. Instead, the manner in which the compound reacts with another serves to identify it as an acid or base.

**AN IMPROVEMENT OVER ITS PREDECESSORS.** The beauty of the Lewis definition lies in the fact that it encompasses all the situations covered by the others—and more. Just as Brønsted-Lowry did not disprove Arrhenius, but rather offered a definition that covered more substances, Lewis expanded the range of substances beyond those covered by Brønsted-Lowry. In particular, Lewis theory can be used to differentiate the acid and base in bond-producing chemical reactions where ions are not produced, and in which there is no proton donor or acceptor. Thus it represents an improvement over Arrhenius and Brønsted-Lowry respectively.

An example is the reaction of boron trifluoride ($BF_3$) with ammonia ($NH_3$), both in the gas phases, to produce boron trifluoride ammonia complex ($F_3BNH_3$). In this reaction, boron trifluoride accepts an electron pair and is therefore a Lewis acid, while ammonia donates the electron pair and is thus a Lewis base. Though hydrogen is involved in this particular reaction, Lewis theory also addresses reactions involving no hydrogen.

# REAL-LIFE APPLICATIONS

## pH and Acid-Base Indicators

Though chemists apply the sophisticated structural definitions for acids and bases that we have discussed, there are also more "hands-on" methods for identifying a particular substance (including complex mixtures) as an acid or base. Many of these make use of the pH scale, developed by Danish chemist Søren Sørensen (1868-1939) in 1909.

The term pH stands for "potential of hydrogen," and the pH scale is a means of determining the acidity or alkalinity of a substance. (Though, as noted, the term "alkali" has been replaced by "base," alkalinity is still used as an adjectival term to indicate the degree to which a substance displays the properties of a base.) There are theoretically no limits to the range of the pH scale, but figures for acidity and alkalinity are usually given with numerical values between 0 and 14.

**THE MEANING OF pH VALUES.** A rating of 0 on the pH scale indicates a substance that is virtually pure acid, while a 14 rating represents a nearly pure base. A rating of 7 indicates a neutral substance. The pH scale is logarithmic, or exponential, meaning that the numbers represent exponents, and thus an increased value of 1 represents not a simple arithmetic addition of 1, but an increase of 1 power. This, however, needs a little further explanation.

The pH scale is actually based on negative logarithms for the values of $H_3O^+$ (the hydronium ion) or $H^+$ (protons) in a given substance. The formula is thus $pH = -\log[H_3O^+]$ or $-\log[H^+]$, and the presence of hydronium ions or protons is measured according to their concentration of moles per liter of solution.

**pH VALUES OF VARIOUS SUBSTANCES.** The pH of a virtually pure acid, such as the sulfuric acid in car batteries, is 0, and this represents 1 mole (mol) of hydronium per liter (l) of solution. Lemon juice has a pH of 2, equal to $10^{-2}$ mol/l. Note that the pH value of 2 translates to an exponent of -2, which, in this case, results in a figure of 0.01 mol/l.

Distilled water, a neutral substance with a pH of 7, has a hydronium equivalent of $10^{-7}$ mol/l. It is interesting to observe that most of the fluids in the human body have pH values in the neutral range blood (venous, 7.35; arterial, 7.45); urine (6.0—note the higher presence of acid); and saliva (6.0 to 7.4).

At the alkaline end of the scale is borax, with a pH of 9, while household ammonia has a pH value of 11, or $10^{-11}$ mol/l. Sodium hydroxide, or lye, an extremely alkaline chemical with a pH of 14, has a value equal to $10^{-14}$ moles of hydronium per liter of solution.

**LITMUS PAPER AND OTHER INDICATORS.** The most precise pH measurements are made with electronic pH meters, which can provide figures accurate to 0.001 pH. However, simpler materials are also used. Best known among these is litmus paper (made from an extract of two lichen species), which turns blue in the presence of bases and red in the presence of acids. The term "litmus test" has become part of everyday language, referring to a make-or-break issue—for example, "views on abortion rights became a litmus test for Supreme Court nominees."

Litmus is just one of many materials used for making pH paper, but in each case, the change of color is the result of the neutralization of the substance on the paper. For instance, paper coated with phenolphthalein changes from colorless to pink in a pH range from 8.2 to 10, so it is useful for testing materials believed to be moderately alkaline. Extracts from various fruits and vegetables, including red cabbages, red onions, and others, are also applied as indicators.

## Some Common Acids and Bases

The tables below list a few well-known acids and bases, along with their formulas and a few applications

Common Acids

- Acetic acid ($CH_3COOH$): vinegar, acetate
- Acetylsalicylic acid ($HOOCC_6H_4OOCCH_3$): aspirin
- Ascorbic acid ($H_2C_6H_6O_6$): vitamin C
- Carbonic acid ($H_2CO_3$): soft drinks, seltzer water
- Citric acid ($C_6H_8O_7$): citrus fruits, artificial flavorings
- Hydrochloric acid (HCl): stomach acid
- Nitric acid ($HNO_3$): fertilizer, explosives
- Sulfuric acid ($H_2SO_4$): car batteries

Common Bases

- Aluminum hydroxide ($Al[OH]_3$): antacids, deodorants
- Ammonium hydroxide ($NH_4OH$): glass cleaner
- Calcium hydroxide ($Ca[OH]_2$): caustic lime, mortar, plaster
- Magnesium hydroxide ($Mg[OH]_2$): laxatives, antacids
- Sodium bicarbonate/sodium hydrogen carbonate ($NaHCO_3$): baking soda
- Sodium carbonate ($Na_2CO_3$): dish detergent
- Sodium hydroxide (NaOH): lye, oven and drain cleaner
- Sodium hypochlorite (NaClO): bleach

Of course these represent only a few of the many acids and bases that exist. Selected substances listed above are discussed briefly below.

## Acids

**ACIDS IN THE HUMAN BODY AND FOODS.** As its name suggests, citric acid is found in citrus fruits—particularly lemons, limes, and grapefruits. It is also used as a flavoring agent, preservative, and cleaning agent. Produced commercially from the fermentation of sugar by several species of mold, citric acid creates a taste that is both tart and sweet. The tartness, of course, is a function of its acidity, or a manifestation of the fact that it produces hydrogen ions. The sweetness is a more complex biochemical issue relating to the ways that citric acid molecules fit into the tongue's "sweet" receptors.

Citric acid plays a role in one famous stomach remedy, or antacid. This in itself is interesting, since antacids are more generally associated with alkaline substances, used for their ability to neutralize stomach acid. The fizz in Alka-Seltzer, however, comes from the reaction of citric acids (which also provide a more pleasant taste) with sodium bicarbonate or baking soda, a base. This reaction produces carbon dioxide gas. As a preservative, citric acid prevents metal ions from reacting with, and thus hastening the degradation of, fats in foods. It is also used in the production of hair rinses and low-pH shampoos and toothpastes.

The carboxylic acid family of hydrocarbon derivatives includes a wide array of substances—not only citric acids, but amino acids. Amino acids combine to make up proteins, one of the principal components in human muscles, skin, and hair. Carboxylic acids are also applied industrially, particularly in the use of fatty acids for making soaps, detergents, and shampoos.

**SULFURIC ACID.** There are plenty of acids found in the human body, including hydrochloric acid or stomach acid—which, in large quantities, causes indigestion, and the need for neutralization with a base. Nature also produces acids that are toxic to humans, such as sulfuric acid.

Though direct exposure to sulfuric acid is extremely dangerous, the substance has numerous applications. Not only is it used in car batteries, but sulfuric acid is also a significant component in the production of fertilizers. On the other hand, sulfuric acid is damaging to the environment when it appears in the form of acid rain. Among the impurities in coal is sulfur, and this results in the production of sulfur dioxide and sulfur trioxide when the coal is burned. 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.

## Bases

The alkali metal and alkaline earth metal families of elements are, as their name suggests, bases. A number of substances created by the reaction of these metals with nonmetallic elements are taken internally for the purpose of settling gastric trouble or clearing intestinal blockage. For instance, there is magnesium sulfate, better known as Epsom salts, which provide a powerful laxative also used for ridding the body of poisons.

Aluminum hydroxide is an interesting base, because it has a wide number of applications, including its use in antacids. As such, it reacts with and neutralizes stomach acid, and for that reason is found in commercial antacids such as Di-Gel™, Gelusil™, and Maalox™. Aluminum hydroxide is also used in water purification, in dyeing garments, and in the production of certain kinds of glass. A close relative, aluminum hydroxychloride or $Al_2(OH)_5Cl$, appears in many commercial antiperspirants, and helps to close pores, thus stopping the flow of perspiration.

**SODIUM HYDROGEN CARBONATE (BAKING SODA).** Baking soda, known by chemists both as sodium bicar-

## KEY TERMS

**ACID:** A substance that, in its edible form, is sour to the taste, and in non-edible forms, is often capable of dissolving metals. Acids and bases react to form salts and water. These are all phenomenological definitions, however, in contrast to the three structural definitions of acids and bases—the Arrhenius, Brønsted-Lowry, and Lewis acid-base theories.

**ALKALI:** A term referring to the soluble hydroxides of the alkali and alkaline earth metals. Once "alkali" was used for the class of substances that react with acids to form salts; today, however, the more general term base is preferred.

**ALKALINITY:** An adjectival term used to identify the degree to which a substance displays the properties of a base.

**ANION:** The negatively charged ion that results when an atom gains one or more electrons. "Anion" is pronounced "AN-ie-un".

**AQUEOUS SOLUTION:** A substance in which water constitutes the solvent. A large number of chemical reactions take place in an aqueous solution.

**ARRHENIUS ACID-BASE THEORY:** The first of three structural definitions of acids and bases. Formulated by Swedish chemist Svante Arrhenius (1859-1927), the Arrhenius theory defines acids and bases according to the ions they produce in an aqueous solution: an acid produces hydrogen ions ($H^+$), and a base hydroxide ions ($OH^-$).

**BASE:** A substance that, in its edible form, is bitter to the taste. Bases tend to be slippery to the touch, and in reaction with acids they produce salts and water. Bases and acids are most properly defined, however, not in these phenomenological terms, but by the three structural definitions of acids and bases—the Arrhenius, Brønsted-Lowry, and Lewis acid-base theories.

**BRØNSTED-LOWRY ACID-BASE THEORY:** The second of three structural definitions of acids and bases. Formulated by English chemist Thomas Lowry (1874-1936) and Danish chemist J. N. Brønsted (1879-1947), Brønsted-Lowry theory defines an acid as a proton ($H^+$) donor, and a base as a proton acceptor.

**CATION:** The positively charged ion that results when an atom loses one or more electrons. "Cation" is pronounced "KAT-ie-un".

**CHEMICAL SPECIES:** A generic term used for any substance studied in chemistry—whether it be an element, compound, mixture, atom, molecule, ion, and so forth.

**CONJUGATE ACID:** An acid formed when a base accepts a proton ($H^+$).

bonate and sodium hydrogen carbonate, is another example of a base with multiple purposes. As noted earlier, it is used in Alka-Seltzer™, with the addition of citric acid to improve the flavor; in fact, baking soda alone can perform the function of an antacid, but the taste is rather unpleasant.

Baking soda is also used in fighting fires, because at high temperatures it turns into carbon dioxide, which smothers flames by obstructing

## KEY TERMS CONTINUED

**CONJUGATE ACID-BASE PAIR:** The acid and base produced when an acid donates a single proton to a base. In the reaction that produces this pair, the acid and base switch identities. By donating a proton, the acid becomes a conjugate base, and by receiving the proton, the base becomes a conjugate acid.

**CONJUGATE BASE:** A base formed when an acid releases a proton.

**ION:** An atom or atoms that has lost or gained one or more electrons, and thus has a net electric charge. There are two types of ions: anions and cations.

**IONIC BONDING:** A form of chemical bonding that results from attractions between ions with opposite electric charges.

**IONIC COMPOUND:** A compound in which ions are present. Ionic compounds contain at least one metal and nonmetal joined by an ionic bond.

**LEWIS ACID-BASE THEORY:** The third of three structural definitions of acids and bases. Formulated by American chemist Gilbert N. Lewis (1875-1946), Lewis theory defines an acid as the reactant that accepts an electron pair from another reactant in a chemical reaction, and a base as the reactant that donates an electron pair to another reactant.

**PH SCALE:** A logarithmic scale for determining the acidity or alkalinity of a substance, from 0 (virtually pure acid) to 7 (neutral) to 14 (virtually pure base).

**PHENOMENOLOGICAL:** A term describing scientific definitions based purely on experimental phenomena. These convey only part of the picture, however—primarily, the part a chemist can perceive either through measurement or through the senses, such as sight. A structural definition is therefore usually preferable to a phenomenological one.

**REACTANT:** A substance that interacts with another substance in a chemical reaction, resulting in the creation of a product.

**SALTS:** Ionic compounds formed by the reaction between an acid and a base. In this reaction, one or more of the hydrogen ions of an acid is replaced with another positive ion. In addition to producing salts, acid-base reactions produce water.

**SOLUTION:** A homogeneous mixture in which one or more substances (the solute) is dissolved in one or more other substances (the solvent)—for example, sugar dissolved in water.

**SOLVENT:** A substance that dissolves another, called a solute, in a solution.

**STRUCTURAL:** A term describing scientific definitions based on aspects of molecular structure and behavior rather than purely phenomenological data.

the flow of oxygen to the fire. Of course, baking soda is also used in baking, when it is combined with a weak acid to make baking powder. The reaction of the acid and the baking soda produces carbon dioxide, which causes dough and batters to rise. In a refrigerator or cabinet, baking soda can absorb unpleasant odors, and additionally, it can be applied as a cleaning product.

**SODIUM HYDROXIDE (LYE).** Another base used for cleaning is sodium

hydroxide, known commonly as lye or caustic soda. Unlike baking soda, however, it is not to be taken internally, because it is highly damaging to human tissue—particularly the eyes. Lye appears in drain cleaners, such as Drano™, and oven cleaners, such as Easy-Off™, which make use of its ability to convert fats to water-soluble soap.

In the process of doing so, however, relatively large amounts of lye may generate enough heat to boil the water in a drain, causing the water to shoot upward. For this reason, it is not advisable to stand near a drain being treated with lye. In a closed oven, this is not a danger, of course; and after the cleaning process is complete, the converted fats (now in the form of soap) can be dissolved and wiped off with a sponge.

## WHERE TO LEARN MORE

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# ACID-BASE REACTIONS

## CONCEPT

To an extent, acids and bases can be defined in terms of factors that are apparent to the senses: edible acids taste sour, for instance, while bases are bitter-tasting and slippery to the touch. The best way to understand these two types of substances, however, is in terms of their behavior in chemical reactions. Not only do the reactions of acids and bases result in the creation of salts and water, but acids and bases can be defined by the ways in which they participate in a reaction—for instance, by donating or accepting electron pairs. The reaction of acids and bases to form water and salts is called neutralization, and it has a wide range of applications, including the promotion of plant growth in soil and the treatment of heartburn in the human stomach. Neutralization also makes it possible to test substances for their pH level, a measure of the degree to which the substance is acidic or alkaline.

## HOW IT WORKS

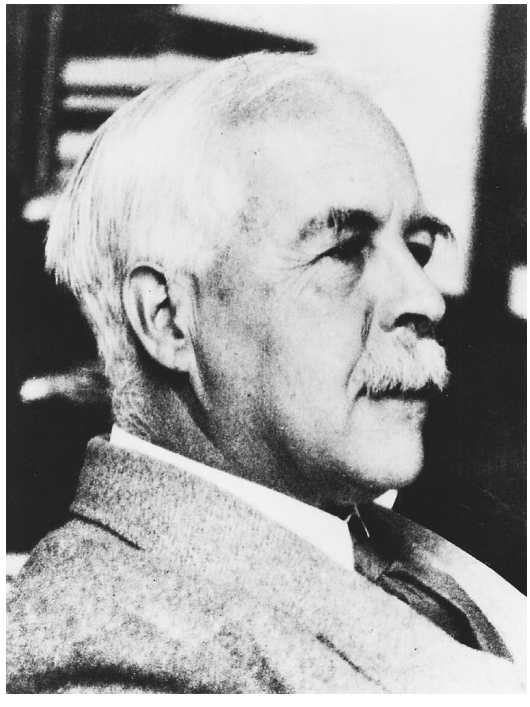
### Phenomenological Definitions of Acids and Bases

Before studying the reactions of acids and bases, it is necessary to define exactly what each is. This is not as easy as it sounds, and the Acids and Bases essay discusses in detail a subject covered more briefly here: the arduous task chemists faced in developing a workable distinction. Let us start with the phenomenological differences between the two—that is, aspects relating to things that can readily be observed without referring to the molecule properties and behaviors of acids and bases.

Acids are fairly easy to understand on the phenomenological level: the name comes from the Latin term *acidus,* or "sour," and many sour substances from daily life—lemons, for instance, or vinegar—are indeed highly acidic. In fact, lemons and most citrus fruits contain citric acid ($C_6H_8O_7$), while the acidic quality of vinegar comes from acetic acid ($CH_3COOH$). In addition, acids produce characteristic colors in certain vegetable dyes, such as those used in making litmus paper.

The word "base," as it is used in this context, may be a bit more difficult to appreciate on a sensory level. It helps, perhaps, if the older term "alkali" is used, though even so, people tend to think of alkaline substances primarily in contrast to acids. "Alkali," which serves to indicate the basic quality of both the alkali metal and alkaline earth metal families of elements, comes from the Arabic *al-qili.* The latter refers to the ashes of the seawort plant, which usually grows in marshy areas and, in the past, was often burned to produce soda ash for making soap.

The reason chemists of today use the word "base" instead of "alkali" is that the latter term has a narrower meaning: all alkalies are bases, but not all bases are alkalies. Originally referring only to the ashes of burned plants containing either sodium or potassium, alkali was eventually used to designate the soluble hydroxides of the alkali and alkaline earth metals. Among these are sodium hydroxide or lye; magnesium hydroxide (found in milk of magnesia); potassium hydroxide, which appears in soaps; and other compounds. Because these represent only a few of the substances that react with acids in the ways discussed in this essay, the term "base" is preferred.



Gilbert N. Lewis.

**THE FORMATION OF SALTS.** As chemistry evolved, and physical scientists became aware of the atomic and molecular substructures that make up the material world, they developed more fundamental distinctions between acids and bases. By the early twentieth century, chemists had applied structural distinctions between acids and bases—that is, definitions based on the molecular structures and behaviors of those substances.

An important intermediary step occurred as chemists came to the conclusion that reactions of acids and bases form salts and water. For instance, in an aqueous solution, hydrochloric acid or HCl(*aq*) reacts with the base sodium hydroxide, designated as NaOH(*aq*), to form sodium chloride, or common table salt (NaCl[*aq*]) and $H_2O$. What happens is that the sodium (Na) ion (an atom with an electric charge) in sodium hydroxide switches places with the hydrogen ion in hydrochloric acid, resulting in the creation of NaCl and water.

Ions themselves had yet to be defined in 1803, when the great Swedish chemist Jons Berzelius (1779-1848) added another piece to the foundation for a structural definition. Acids and bases, he suggested, have opposite electric charges. In this, he was about eight decades ahead of his time: only in 1884 did his countryman Svante Arrhenius (1859-1927) introduce the concept of the ion. This, in turn, enabled Arrhenius to formulate the first structural distinction between acids and bases.

## The Arrhenius Acid-Base Theory

Arrhenius acid-base theory defines the two substances with regard to their behavior in an aqueous solution: an acid is any compound that produces hydrogen ions ($H^+$), and a base is one that produces hydroxide ions ($OH^-$) when dissolved in water. This occurred, for instance, in the reaction discussed above: the hydrochloric acid produced a hydrogen ion, while the sodium hydroxide produced a hydroxide ion, and these two ions bonded to form water.

Though it was a good start, Arrhenius's theory was limited to reactions in aqueous solutions. In addition, it confined its definition of acids and bases only to those ionic compounds, such as hydrochloric acid or sodium hydroxide, that produced either hydrogen or hydroxide ions. But ammonia, or $NH_3$, acts like a base in aqueous solutions, even though it does not produce the hydroxide ion. These shortcomings pointed to the need for a more comprehensive theory, which came with the formulation of the Brønsted-Lowry definition.

## The Brønsted-Lowry Acid-Base Theory

Developed by English chemist Thomas Lowry (1874-1936) and Danish chemist J. N. Brønsted (1879-1947), the Brønsted-Lowry acid-base theory defines an acid as a proton ($H^+$) donor, and a base as a proton acceptor, in a chemical reaction. Protons are represented by the symbol $H^+$, a cation (positively charged ion) of hydrogen.

Elemental hydrogen, called protium to distinguish it from its isotopes, has just one proton and one electron—no neutrons. Therefore, the hydrogen cation, which has to lose its sole electron to gain a positive charge, is essentially nothing but a proton. It is thus at once an atom, an ion, and a proton, but the ionization of hydrogen constitutes the only case in which this is possible.

Thus when the term "proton donor" or "proton acceptor" is used, it does not mean that a proton is splitting off from an atom or joining

another, as in a nuclear reaction. Rather, when an acid behaves as a proton donor, this means that the hydrogen proton/ion/atom is separating from an acidic compound; conversely, when a base acts as a proton acceptor, the positively charged hydrogen ion is bonding with the basic compound.

**REACTIONS IN BRØNSTED-LOWRY ACID-BASE THEORY.** In representing Brønsted-Lowry acids and bases, the symbols HA and $A^-$, respectively, are used. These appear in the equation representing the most fundamental type of Brønsted-Lowry acid-base reaction: $HA(aq) + H_2O(l) \rightarrow H_3O^+(aq) + A^-(aq)$. The symbols (*aq*), (*l*), and → are explained in the Chemical Reactions essay. In plain English, this equation states that when an acid in an aqueous solution reacts with liquid water, the result is the creation of $H_3O^+$, known as the hydronium ion, along with a base. Both products of the reaction are dissolved in an aqueous solution.

Because water molecules are polar, the negative charges tend to congregate on one end of the molecule with the oxygen atom, while the positive charges remain on the other end with the hydrogen atoms. The Brønsted-Lowry model emphasizes the role played by water, which pulls the proton from the acid, resulting in the creation of the hydronium ion.

The hydronium ion, in this equation, is an example of a conjugate acid, an acid formed when a base accepts a proton. At the same time, the acid has lost its proton, becoming $A^-$, a conjugate base—that is, the base formed when an acid releases a proton. These two products of the reaction are called a conjugate acid-base pair, a term that refers to two substances related to one another by the donating of a proton.

Brønsted and Lowry's definition includes all Arrhenius acids and bases, as well as other chemical species not encompassed in Arrhenius theory. As mentioned earlier, ammonia is a base, yet it does not produce $OH^-$ ions; however, it does accept a proton from a water molecule. Water can serve either as an acid or base; in this instance, it is an acid, and in reaction with ammonia, it produces the conjugate acid-base pair of $NH_4^+$ (an ammonium ion) and $OH^-$. Ammonia did not produce the hydroxide ion here; rather, $OH^-$ is the conjugate base that resulted when the water molecule lost its $H^+$ atom (i.e., a proton.)

### THE LEWIS ACID-BASE THEORY

The Brønsted-Lowry model still had its limitations, in that it only described compounds containing hydrogen. American chemist Gilbert N. Lewis (1875-1946), however, developed a theory of acids and bases that makes no reference to the presence of hydrogen. Instead, it relates to something much more fundamental: the fact that chemical bonding always involves pairs of electrons.

Lewis acid-base theory defines an acid as the reactant that accepts an electron pair from another reactant in a chemical reaction, while a base is the reactant that donates an electron pair to another reactant. Note that, as with the Brønsted-Lowry definition, the Lewis definition is reaction-dependant. Instead of defining a compound as an acid or base in its own right, it identifies these in terms of how the compound reacts with another.

The Lewis definition encompasses all the situations covered by the others, as well as many other reactions not described in the theories of either Arrhenius or Brønsted-Lowry. In particular, Lewis theory can be used to differentiate the acid and base in chemical reactions where ions are not produced, something that takes it far beyond the scope of Arrhenius theory. Also, Lewis theory addresses situations in which there is no proton donor or acceptor, thus offering an improvement over Brønsted-Lowry.

When boron trifluoride ($BF_3$) and ammonia ($NH_3$), both in the gas phases, react to produce boron trifluoride ammonia complex ($F_3BNH_3$), boron trifluoride accepts an electron pair. Therefore, it is a Lewis acid, while ammonia—which donates the electron pair—can be defined as a Lewis base. This particular reaction involves hydrogen, but since the operative factor in Lewis theory relates to electron pairs and not hydrogen, the theory can be used to address reactions in which that element is not present.

## REAL-LIFE APPLICATIONS

### DISSOCIATION

Dissociation is the separation of a molecule into ions, and it is a key factor for evaluating the "strength" of acids and bases. The more a substance is prone to dissociation, the better it can

conduct an electric current, because the separation of charges provides a "pathway" for the current's flow. A substance that dissociates completely, or almost completely, is called a strong electrolyte, whereas one that dissociates only slightly (or not at all) is designated as a weak electrolyte.

The terms "weak" and "strong" are also applied to acids and bases. For instance, vinegar is a weak acid, because it dissociates only slightly, and therefore conducts little electric current. By contrast, hydrochloric acid (HCl) is a strong acid, because it dissociates almost completely into positively charged hydrogen ions and negatively charged chlorine ones. Represented symbolically, this is: $HCl \rightarrow H^+ + Cl^-$.

**A REACTION INVOLVING A STRONG ACID.** It may seem a bit backward that a strong acid or base is one that "falls apart," while the weak one stays together. To understand the difference better, let us return to the reaction described earlier, in which an acid in aqueous solution reacts with water to produce a base in aqueous solution, along with hydronium: $HA(aq) + H_2O(l) \rightarrow H_3O^+(aq) + A^-(aq)$. Instead of using the generic symbols HA and $A^-$, however, let us substitute hydrochloric acid (HCl) and chloride ($Cl^-$) respectively.

The reaction $HCl(aq) + H_2O(l) \rightarrow H_3O^+(aq) + Cl^-(aq)$ is a reversible one, and for that reason, the symbol for chemical equilibrium ($\leftrightharpoons$) can be inserted in place of the arrow pointing to the right. In other words, the substances on the right can just as easily react, producing the substances on the left. In this reverse reaction, the reactants of the forward reaction would become products, and the products of the forward reaction serve as the reactants.

However, the reaction described here is not perfectly reversible, and in fact the most proper chemical symbolism would show a longer arrow pointing to the right, with a shorter arrow pointing to the left. Due to the presence of a strong electrolyte, there is more forward "thrust" to this reaction.

Because it is a strong acid, the hydrogen chloride in solution is not a set of molecules, but a collection of $H^+$ and $Cl^-$ ions. In the reaction, the weak $Cl^-$ ions to the right side of the equilibrium symbol exert very little attraction for the $H^+$ ions. Instead of bonding with the chloride, these hydrogen ions join the water (a stronger base) to form hydronium.

The chloride, incidentally, is the conjugate base of the hydrochloric acid, and this illustrates another principal regarding the "strength" of electrolytes: a strong acid produces a relatively weak conjugate base. Likewise, a strong base produces a relatively weak conjugate acid.

**THE STRONG ACIDS AND BASES.** There are only a few strong acids and bases, which are listed below:

Strong Acids

- Hydrobromic acid (HBr)
- Hydrochloric acid (HCl)
- Hydroiodic acid (HI)
- Nitric acid ($HNO_3$)
- Perchloric acid ($HClO_4$)
- Sulfuric acid ($H_2SO_4$)

Strong Bases

- Barium hydroxide ($Ba[OH]_2$)
- Calcium hydroxide ($Ca[OH]_2$)
- Lithium hydroxide (LiOH)
- Potassium hydroxide (KOH)
- Sodium hydroxide (NaOH)
- Strontium hydroxide ($Sr[OH]_2$)

Virtually all others are weak acids or bases, meaning that only a small percentage of molecules in these substances ionize by dissociation. The concentrations of the chemical species involved in the dissociation of weak acids and bases are mathematically governed by the equilibrium constant *K*..

## Neutralization

Neutralization is the process whereby an acid and base react with one another to form a salt and water. The simplest example of this occurs in the reaction discussed earlier, in which hydrochloric acid or $HCl(aq)$ reacts with the base sodium hydroxide, designated as $NaOH(aq)$, in an aqueous solution. The result is sodium chloride, or common table salt ($NaCl[aq]$) and $H_2O$. This equation is written thus: $HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O$.

The human stomach produces hydrochloric acid, commonly known as "stomach acid." It is generated in the digestion process, but when a person eats something requiring the stomach to work overtime in digesting it—say, a pizza—the stomach may generate excess hydrochloric acid,

and the result is "heartburn." When this happens, people often take antacids, which contain a base such as aluminum hydroxide ($Al[OH]_3$) or magnesium hydroxide ($Mg[OH]_2$).

When a person takes an antacid, the reaction leads to the creation of *a* salt, but not the salt with which most people are familiar—NaCl. As shown above, that particular salt is the product of a reaction between hydrochloric acid and sodium hydroxide, but a person who ingested sodium hydroxide (a substance used to unclog drains and clean ovens) would have much worse heartburn than before! In any case, the antacid reacts with the stomach acid to produce a salt, as well as water, and thus the acid is neutralized.

When land formerly used for mining is reclaimed, the acidic water in the area must be neutralized, and the use of calcium oxide (CaO) as a base is one means of doing so. Acidic soil, too, can be neutralized by the introduction of calcium carbonate ($CaCO_3$) or limestone, along with magnesium carbonate ($MgCO_3$). If soil is too basic, as for instance in areas where there has been too little precipitation, acid-like substances such as calcium sulfate or gypsum ($SaSO_4$) can be used. In either case, neutralization promotes plant growth.

**TITRATION AND PH.** One of the most important applications of neutralization is in titration, the use of a chemical reaction to determine the amount of a chemical substance in a sample of unknown purity. In a typical form of neutralization titration, a measured amount of an acid is added to a solution containing an unknown amount of a base. Once enough of the acid has been added to neutralize the base, it is possible to determine how much base exists in the solution.

Titration can also be used to measure pH ("power of hydrogen") level by using an acid-base indicator. The pH scale assigns values ranging from 0 (a virtually pure acid) to 14 (a virtually pure base), with 7 indicating a neutral substance. An acid-base indicator such as litmus paper changes color when it neutralizes the solution.

The transition interval (the pH at which the color of an indicator changes) is different for different types of indicators, and thus various indicators are used to measure substances in specific pH ranges. For instance, methyl red changes from red to yellow across a pH range of 4.4 to 6.2, so it is most useful for testing a substance suspected of being moderately acidic.

**BUFFERED SOLUTIONS.** A buffered solution is one that resists a change in pH even when a strong acid or base is added to it. This buffering results from the presence of a weak acid and a strong conjugate base, and it can be very important to organisms whose cells can endure changes only within a limited range of pH values. Human blood, for instance, contains buffering systems, because it needs to be at pH levels between 7.35 and 7.45.

The carbonic acid-bicarbonate buffer system is used to control the pH of blood. The most important chemical equilibria (that is, reactions involving chemical equilibrium) for this system are: $H^+ + HCO_3^- \leftrightharpoons H_2CO_3 \leftrightharpoons H_20 + CO_2$. In other words, the hydrogen ion ($H^+$) reacts with the hydrogen carbonate ion ($HCO_3^-$) to produce carbonic acid ($H_2CO_3$). The latter is in equilibrium with the first set of reactants, as well as with water and carbon dioxide in the forward reaction.

The controls the pH level by changing the concentration of carbon dioxide by exhalation. In accordance with Le Châtelier's principle, this shifts the equilibrium to the right, consuming $H^+$ ions. In normal blood plasma, the concentration of $HCO_3^-$ is about 20 times as great as that of $H_2CO_3$, and this large concentration of hydrogen carbonate gives the buffer a high capacity to neutralize additional acid. The buffer has a much lower capacity to neutralize bases because of the much smaller concentration of carbonic acid.

## WATER: BOTH ACID AND BASE

Water is an amphoteric substance; in other words, it can serve either as an acid or a base. When water experiences ionization, one water molecule serves as a Brønsted-Lowry acid, donating a proton to another water molecule—the Brønsted-Lowry base. This results in the production of a hydroxide ion and a hydronium ion: $H_2O(l) + H_2O(l) \leftrightharpoons H_3O^+(aq) + OH^-(aq)$.

This equilibrium equation is actually one in which the tendency toward the reverse reaction is much greater; therefore the equilibrium symbol, if rendered in its most proper form, would show a much shorter arrow pointing toward the right. In water purified by distillation, the concentra-

## KEY TERMS

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**ALKALI:** A term referring to the soluble hydroxides of the alkali and alkaline earth metals. Once "alkali" was used for the class of substances that react with acids to form salts; today, however, the more general term base is preferred.

**ALKALINITY:** An adjectival term used to identify the degree to which a substance displays the properties of a base.

**AMPHOTERIC:** A term describing a substance that can serve either as an acid or a base. Water is the most significant amphoteric substance.

**AQUEOUS SOLUTION:** A substance in which water constitutes the solvent. A large number of chemical reactions take place in an aqueous solution.

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**BASE:** A substance that in its edible form is bitter to the taste. Bases tend to be slippery to the touch, and in reaction with acids they produce salts and water. Bases and acids are most properly defined, however, not in these phenomenological terms, but by the three structural definitions of acids and bases—the Arrhenius, Brønsted-Lowry, and Lewis acid-base theories.

**BASIC:** In the context of acids and bases, the word is the counterpart to "acidic," identifying the base-like quality of a substance.

**BRØNSTED-LOWRY ACID-BASE THEORY:** The second of three structural definitions of acids and bases. Formulated by English chemist Thomas Lowry (1874-1936) and Danish chemist J. N. Brønsted (1879-1947), Brønsted-Lowry theory defines an acid as a proton ($H^+$) donor, and a base as a proton acceptor.

**CHEMICAL SPECIES:** A generic term used for any substance studied in chemistry—whether it be an element, compound, mixture, atom, molecule, ion, and so forth.

**CONJUGATE ACID:** An acid formed when a base accepts a proton ($H^+$).

**CONJUGATE ACID-BASE PAIR:** The acid and base produced when an acid donates a single proton to a base. In the reaction that produces this pair, the acid and base switch identities. By donating a proton, the acid becomes a conjugate base, and by receiving the proton, the base becomes a conjugate acid.

**CONJUGATE BASE:** A base formed when an acid releases a proton.

**DISSOCIATION:** The separation of molecules into ions.

## KEY TERMS CONTINUED

**ION:** An atom or atoms that has lost or gained one or more electrons, and thus has a net electric charge. There are two types of ions: anions and cations.

**IONIC BONDING:** A form of chemical bonding that results from attractions between ions with opposite electric charges.

**IONIC COMPOUND:** A compound in which ions are present. Ionic compounds contain at least one metal and nonmetal joined by an ionic bond.

**LEWIS ACID-BASE THEORY:** The third of three structural definitions of acids and bases. Formulated by American chemist Gilbert N. Lewis (1875-1946), Lewis theory defines an acid as the reactant that accepts an electron pair from another reactant in a chemical reaction, and a base as the reactant that donates an electron pair to another reactant.

**NEUTRALIZATION:** The process whereby an acid and base react with one another to form a salt and water.

**PH SCALE:** A logarithmic scale for determining the acidity or alkalinity of a substance, from 0 (virtually pure acid) to 7 (neutral) to 14 (virtually pure base).

**PHENOMENOLOGICAL:** A term describing scientific definitions based purely on experimental phenomena. These only convey part of the picture, however—primarily, the part a chemist can perceive either through measurement or through the senses, such as sight. A structural definition is therefore usually preferable to a phenomenological one.

**REACTANT:** A substance that interacts with another substance in a chemical reaction, resulting in the creation of a product.

**SALTS:** Ionic compounds formed by the reaction between an acid and a base. In this reaction, one or more of the hydrogen ions of an acid is replaced with another positive ion. In addition to producing salts, acid-base reactions produce water.

**SOLUTION:** A homogeneous mixture in which one or more substances (the solute) is dissolved in another substance (the solvent)—for example, sugar dissolved in water.

**SOLVENT:** A substance that dissolves another, called a solute, in a solution.

**STRONG ELECTROLYTE:** A substance highly prone to dissociation. The terms "strong acid" or "strong base" refers to those acids or bases which readily dissociate.

**STRUCTURAL:** A term describing scientific definitions based on aspects of molecular structure and behavior rather than purely phenomenological data.

**TITRATION:** The use of a chemical reaction to determine the amount of a chemical substance in a sample of unknown purity. Testing pH levels is an example of titration.

**TRANSITION INTERVAL:** The pH level at which the color of an acid-base indicator changes.

**WEAK ELECTROLYTE:** A substance that experiences little or no dissociation. The terms "weak acid" or "weak base" refer to those acids or bases not prone to dissociation.

tions of hydronium ($H_3O^+$) and hydroxide ($OH^-$) ions are equal. When multiplied by one another, these yield the constant figure $1.0 \cdot 10^{-14}$, which is the equilibrium constant for water. In fact, this constant—denoted as $K_w$—is called the ion-product constant for water.

Because the product of these two concentrations is always the same, this means that if one of them goes up, the other one must go down in order to yield the same constant. This explains the fact, noted earlier, that water can serve either as an acid or base—or, if the concentrations of hydronium and hydroxide ions are equal—as a neutral substance. In situations where the concentration of hydronium is higher, and the hydroxide concentration automatically decreases, water serves as an acid. Conversely, when the hydroxide concentration is high, the hydronium concentration decreases correspondingly, and the water is a base.

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# SOLUTIONS AND MIXTURES

MIXTURES

SOLUTIONS

OSMOSIS

DISTILLATION AND FILTRATION

# MIXTURES

## CONCEPT

Elements and compounds are pure substances, but much of the material around us—including air, wood, soil, and even (in most cases) water—appears in the form of a mixture. Unlike a pure substance, a mixture has variable composition: in other words, it cannot be reduced to a single type of atom or molecule. Mixtures can be either homogeneous—that is, uniform in appearance, and having only one phase—or heterogeneous, meaning that the mixture is separated into various regions with differing properties. Most homogeneous mixtures are also known as solutions, and examples of these include air, coffee, and even metal alloys. As for heterogeneous mixtures, these occur, for instance, when sand or oil are placed in water. Oil can, however, be dispersed in water as an emulsion, with the aid of a surfactant or emulsifier, and the result is an almost homogeneous mixture. Another interesting example of a heterogeneous mixture occurs when colloids are suspended in fluid, whether that fluid be air or water.

## HOW IT WORKS

### Mixtures and Pure Substances

A mixture is a substance with a variable composition, meaning that it is composed of molecules or atoms of differing types. These may have intermolecular bonds, or bonds between molecules, but such bonds are not nearly as strong as those formed when elements bond to form a compound.

Examples of mixtures include milk, coffee, tea, and soft drinks—indeed, they include virtually any drink except for pure water, which is a rarity, because water is highly soluble and tends to contain minerals and other impurities. Air, too, is a mixture, because it contains oxygen, nitrogen, noble gases, carbon dioxide, and water vapor. Likewise metal alloys such as bronze, brass, and steel are mixtures.

**STRUCTURAL AND PHENOMENOLOGICAL DISTINCTIONS.** Before chemists accepted the atomic theory of matter, it was often difficult to distinguish a mixture, such as air or steel, from pure substances, which have the same composition throughout. Pure substances are either elements such as oxygen or iron, or compounds—for example, carbon dioxide or iron oxide. An element is made up of only one type of atom, while a compound can be reduced to one type of bonded chemical species—usually either a molecule or a formation of ions.

A distinction between mixtures and pure substances based on atomic and molecular structures is called, fittingly enough, a structural definition. Prior to the development of atomic theory by English chemist John Dalton (1766-1844), and the subsequent identification of molecules by Italian physicist Amedeo Avogadro (1776-1856), chemists defined compounds and mixtures on the basis of phenomenological data garnered through observation and measurement. This could and did lead to incorrect suppositions.

**PROUST AND THE DEBATE OVER CONSTANT COMPOSITION.** Around the time of Dalton and Avogadro, French



The wondrous invention known as soap is a mixture with surfactant qualities. *(Chad Weckler/Corbis. Reproduced by permission.)*

chemist Antoine Lavoisier (1743-1794) correctly identified an element as a substance that could not be broken down into a simpler substance. Later, his countryman Joseph-Louis Proust (1754-1826) clarified the definition of a compound, stating it in much the same terms that we have used: the composition of a compound is the same throughout. But with the very rudimentary knowledge of atoms and molecules that chemists of the early nineteenth century possessed, the distinctions between compounds and mixtures remained elusive.

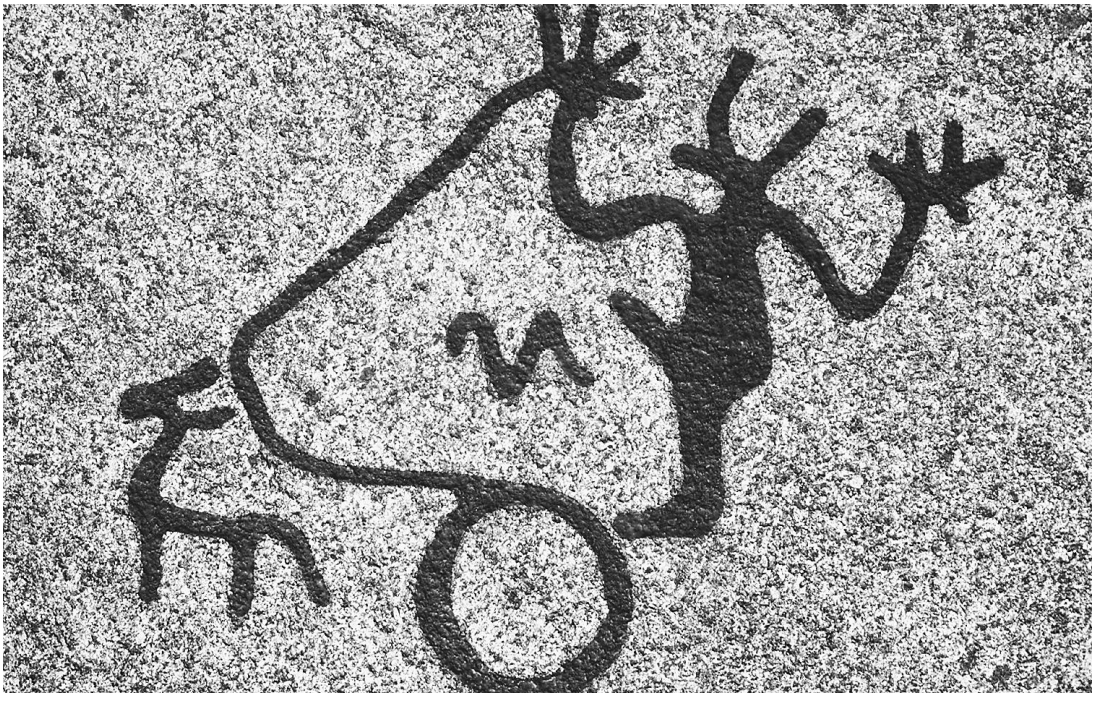
Proust's contemporary and intellectual rival Claude Louis Berthollet (1748-1822) observed that when metals such as iron are heated, they form oxides in which the percentage of oxygen increases with temperature. If constant composition is a fact, he challenged Proust, then how is this possible? Proust maintained that the proportions of elements in a compound are always the same, a hypothesis Berthollet countered by observing that metals can form variable alloys. Bronze, for instance, is an alloy of tin and copper at a ratio of about 25:75, but if the ratio were changed to, say, 30:70, it would still be called bronze.

At the time, the equipment—both in terms of knowledge and tools for analysis—simply did not exist whereby Berthollet's assertions could be successfully proven wrong. Indeed, Berthollet, a student of Lavoisier who contributed to progress in the study of acids and reactants, was no anti-scientific villain: he was simply responding to the evidence as he saw it. Only with the discovery of subatomic particles in the late nineteenth and early twentieth centuries, discoveries that changed the entire character of chemistry as a discipline, did it truly become possible to answer Berthollet's challenges.

Chemists now understand that the oxide formed on the surface of a metal is a compound separate from the metal itself, and that alloys (discussed later in this essay) are not compounds at all: they are mixtures.

## Mixtures and Compounds

With our modern knowledge of atomic and molecular properties, we can more fully distinguish between a compound and a mixture. First, a mixture can exist in virtually any proportion among its constituent parts, whereas a compound has a definite and constant composition. Coffee, whether weak or strong, is still coffee, but if a second oxygen atom chemically bonds to the oxygen in carbon monoxide (CO), the resulting



Bronze—an alloy of tin and copper—was one of the most important inventions in human history. This stone carving is from the period known as the Bronze Age. *(Kevin Schafer/Corbis. Reproduced by permission.)*

compound is not simply "strong carbon monoxide" or even "oxygenated carbon monoxide": it is carbon dioxide ($CO_2$), an entirely different substance. The difference is enormous: carbon dioxide is a part of the interactions between plant and animal life that sustains the natural environment, whereas carbon monoxide is a toxic gas produced, for instance, by automobiles.

Second, the parts of a mixture retain most of their properties when they join together, but elements lose their elemental characteristics once they form a compound. Sugar is still sweet, regardless of the substance into which it is dissolved. In coffee or another drink, it may no longer be dry and granular, though it could be returned to that state by evaporating the coffee. In any case, dryness and granularity are physical properties, whereas sweetness is a chemical one. On the other hand, when elemental carbon bonds with hydrogen and oxygen to form sugar itself, the resulting compound is nothing like the elements from which it is made.

Third, a mixture can usually be created simply by the physical act of stirring items together, and/or by applying heat. As discussed below, relatively high temperatures are sometimes needed to dissolve sugar in tea, for instance; likewise, alloys are usually formed by heating metals to much higher temperatures. On the other hand, the formation of a compound involves a chemical reaction, a vastly more complex interaction than the one required to create a mixture. Carbon, a black solid found in coal, can be mixed with hydrogen and oxygen—both colorless and odorless gases—and the resulting mess would be something; but it would not be sugar. Only the chemical reaction between the three elements, in specific proportions and under specific conditions, results in their chemical bonding to form table sugar, known to chemists as sucrose.

## Homogeneous and Heterogeneous Mixtures

**Homogeneous mixtures and solutions.** As we have seen, the composition of a mixture is variable. Coffee, for instance, can be weak or strong, and milk can be "whole" or low-fat. Beer can be light or dark in color, as well as "light" in terms of calorie content; furthermore, its alcohol content can be varied, as with all alcoholic drinks. Though their molecular composition is variable, each of the mixtures described here is the same throughout: in other words, there is no difference between one region and another in a glass of beer. Such a mixture is described as homogeneous.

A homogeneous mixture is one that is the same throughout, but this is not the same as saying that a compound has a constant composition. Rather, when we say that a homogeneous mixture is the same in every region, we are speaking phenomenologically rather than structurally. From the standpoint of ordinary observation, a glass of milk is uniform, but as we shall see, milk is actually a type of emulsion, in which one substance is dispersed in another. There are no milk "molecules," and structural analysis would reveal that milk does not have a constant molecular composition.

Coffee is an example of a solution, a specific type of homogeneous mixture. Actually, most homogeneous mixtures can be considered solutions, but since a solution is properly defined as a homogeneous mixture in which one or more substances is dissolved in another substance, a 50:50 homogeneous mixture is technically not a solution. When particles are perfectly dissolved in a solution, the composition is uniform, but again, this is not a compound, because that composition can always be varied.

**HETEROGENEOUS MIXTURES.** Anyone who has ever made iced tea has observed that it is easy to sweeten when it is hot, because temperature affects the ability of a solvent such as water—in this case, water with particles from tea leaves filtered into it—to dissolve a solute, such as sugar. Cold tea, on the other hand, is much harder to sweeten with ordinary sugar. Usually what happens is that, instead of obtaining a homogeneous mixture, the result is heterogeneous.

Whereas every region within a homogeneous mixture is more or less the same as every other region, heterogeneous mixtures contain regions that differ from one another. In the example we have used, a glass of cold tea with undissolved sugar at the bottom is a heterogeneous mixture: the tea at the top is unsweetened or even bitter, whereas at the bottom, there is an overly sweet sludge of tea and sugar.

**FROM HOMOGENEOUS TO HETEROGENEOUS AND BACK AGAIN.** The distinction between homogeneous and heterogeneous solutions only serves to further highlight the difference between compounds and mixtures. Whereas the composition of a compound is definite and quantitative (so many atoms of element x bonded with so many atoms of element y in such-and-such a structure), there is less of a sharp dividing line between homogeneous and heterogeneous solutions.

When too much of a solute is added to the solvent, the solvent becomes saturated, and is no longer truly homogeneous. Such is the case when the sugar drifts to the bottom of the tea, or when coffee grounds form in the bottom of a coffee pot containing an otherwise uniform mixture of coffee and water.

Milk comes to us as a homogeneous substance, thanks to the process of homogenization, but when it comes out of the cow, it is a more heterogeneous mixture of milk fat and water. In fact, milk is an example of an emulsion, the result of a process whereby two substances that would otherwise form a heterogeneous mixture are made to form a homogeneous one.

## REAL-LIFE APPLICATIONS

### COLLOIDS

In 1827, Scottish naturalist Robert Brown (1773-1858) was studying pollen grains under a microscope when he noticed that the grains underwent a curious zigzagging motion in the water. At first, he assumed that the motion had a biological explanation—in other words, that it resulted from life processes within the pollen—but later, he discovered that even pollen from long-dead plants behaved in the same way.

What Brown had observed was the suspension of a colloid—a particle intermediate in size between a molecule and a speck of dust—in the water. When placed in water or another fluid (both liquids and gases are called "fluids" in the physical sciences), a colloid forms a mixture similar both to a solution and a suspension. As with a solution, the composition remains homogeneous—the particles never settle to the bottom of the container. At the same time, however, the particles remain suspended rather than dissolved, rendering a cloudy appearance to the dispersion.

Almost everyone, especially as a child, has been fascinated by the colloidal dispersion of dust particles in a beam of sunlight. They seem to be continually in motion, as indeed they are, and this movement is called "Brownian motion" in

honor of the man who first observed it. Yet Brown did not understand what he was seeing; only later did scientists recognize that Brownian motion is the result of movement on the part of molecules in a fluid. Even though the molecules are much smaller than the colloid, there are enough of them producing enough collisions to cause the colloid to be in constant motion.

Another remarkable aspect of dust particles floating in sunlight is the way that they cause a column of sunlight to become visible. This phenomenon, called the Tyndall effect after English physicist John Tyndall (1820-1893), makes it seem as though we are actually seeing a beam of light. In fact, what we are seeing is the reflection of light off the colloidal dispersion. Another example of a colloidal dispersion occurs when a puff of smoke hangs in the air; furthermore, as we shall see, milk is a substance made up of colloids—in this case, particles of fat and protein suspended in water.

## Emulsions

Miscibility is a qualitative term identifying the relative ability of two substances to dissolve in one another. Generally, water and water-based substances have high miscibility with regard to one another, as do oil and oil-based substances with one another. Oil and water, on the other hand (or substances based in either) have very low miscibility.

The reason is that water molecules are polar, meaning that the positive electric charge is in one region of the molecule, while the negative charge is in another region. Oil, on the other hand, is nonpolar, meaning that charges are more evenly distributed throughout the molecule. Trying to mix oil and water is thus rather like attempting to use a magnet to attract a nonmagnetic metal such as gold.

**HOW SURFACTANTS AID THE EMULSION PROCESS.** An emulsion is a mixture of two immiscible liquids such as oil and water—we will use these simple terms, with the idea that these stand for all oil- and water-soluble substances—by dispersing microscopic droplets of one liquid in another. In order to achieve this dispersion, there needs to be a "middle man," known as an emulsifier or surfactant. The surfactant, made up of molecules that are both water- and oil-soluble, acts as an agent for joining other substances in an emulsion.

All liquids have a certain degree of surface tension. This is what causes water on a hard surface to bead up instead of lying flat. (Mercury has an extremely high surface tension.) Surfactants break down this surface tension, enabling the marriage of two formerly immiscible liquids.

In an emulsion, millions of surfactants surround the dispersed droplets (known as the internal phase), shielding them from the other liquid (the external phase). Supposing oil is the internal phase, then the oil-soluble end of the surfactant points toward the oils, while the water-soluble side joins with the water of the external phase.

**PHYSICAL CHARACTERISTICS OF AN EMULSION.** The resulting emulsion has physical (as opposed to chemical) properties different from those of the substances that make it up. Water and most oils are transparent, whereas emulsions are typically opaque and may have a lustrous, pearly gleam. Oil and water flow freely, but emulsions can be made to form thick, non-flowing creams.

Emulsions are inherently unstable: they are, as it were, only temporarily homogeneous. A good example of this is an oil-and-vinegar salad dressing, which has to be shaken before putting it on salad; otherwise, what comes out of the bottle is likely to be mainly oil, which floats to the top of the water-based vinegar. It is characteristic of emulsions that eventually gravity pulls them apart, so that the lighter substances float to the top. This process may take only a few minutes, as with the salad dressing; on the other hand, it can take thousands of years.

**APPLICATIONS.** Surfactants themselves are often used in laundry or dish detergent, because most stains on plates or clothes are oil-based, whereas the detergent itself is applied to the clothes in an aqueous solution. As for emulsions, these are found in a wide variety of products, from cosmetics to paint to milk.

In the pharmaceutical industry, for instance, emulsions are used as a means of delivering the active ingredients of drugs, many of which are not water soluble, in a medium that is. Pharmaceutical manufacturers also use emulsions to make medicines more palatable (easier to take); to control dosage and improve effectiveness; and to improve the usefulness of topical drugs such as ointments, which must contend with both oily and water-soluble substances on the skin.

The oils and other conditioning agents used in hair-care products would leave hair limp and sticky if applied by themselves. Instead, these products are applied in emulsions that dilute the oils in other materials. Emulsions are also used in color photography, as well as in the production of pesticides and fungicides.

Paints and inks, too, are typically emulsified substances, and these sometimes come in the form of dispersions akin to those of colloids. As we have seen, in a dispersion fine particles of solids are suspended in a liquid. Surfactants are used to bond the particles to the liquid, though paint must be shaken, usually with the aid of a high-speed machine, before it is consistent enough to apply.

As mentioned earlier, milk is a form of emulsion that contains particles of milk fat or cream dispersed in water. Light strikes the microscopic fat and protein colloids, resulting in the familiar white color. Other examples of emulsified foods include not only salad dressings, but gravies and various sauces, peanut butter, ice cream, and other items. Not only does emulsion affect the physical properties of foods, but it may enhance the taste by coating the tongue with emulsified oils.

## SOAP

The wondrous invention called soap, which has made the world a cleaner place, exhibits several of the properties we have discussed. It is a mixture with surfactant qualities, and in powdered form, it can form something close to a true solution with water. Discovered probably by the Phoenicians around 600 B.C., it was made in ancient times by boiling animal fat (tallow) or vegetable oils with an alkali or base of wood ashes.

This was a costly process, and for many centuries, only the wealthy could afford soap—a fact that contributed to the notorious lack of personal hygiene that prevailed among Europeans of the Middle Ages. In fact, the situation did not change until late in the eighteenth century, when the work of two French chemists yielded a more economical manufacturing method.

In 1790, Nicholas Leblanc (1742-1806) developed a process for creating sodium hydroxide (called caustic soda at the time) from sodium chloride, or ordinary table salt. This made for an inexpensive base or alkali, with which soap manufacturers could combine natural fats and oils. Then in 1823, Michel Eugène Chevreul (1786-1889) showed that fat is a compound of glycerol with organic acids, a breakthrough that led to the use of fatty acids in producing soaps.

**THE CHEMISTRY OF SOAP.** Soap as it is made today comes from a salt of an alkali metal, such as sodium or potassium, combined with a mixture of carboxylic acids ("fatty acids"). These carboxylic acids are the result of a reaction called saponification, involving triglycerides and a base, such as sodium hydroxide. Saponification breaks the triglycerides into their component fatty acids; then, the base neutralizes these to salts. This reaction produces glycerin, a hydrocarbon bonded to a hydroxyl (-OH) group. (Hydrocarbons are discussed in the essays on Organic Chemistry; Polymers.)

In general, the formula for soap is RCOOX, where X stands for the alkali metals, and R for the hydrocarbon chain. Because it is a salt (meaning that it is formed from the reaction of an acid with a base), soap partially separates into its component ions in water. The active ion is RCOO-, whose two ends behave in different fashions, making it a surfactant. The hydrocarbon end (R-) is said to be lipophilic, or "oil-loving," which is appropriate, since most oils are hydrocarbons. On the other hand, the carboxylate end (-COO-) is hydrophilic, or "water-loving." As a result, soap can dissolve in water, but can also clean greasy stains.

When soap is mixed with water, it does not form a true homogeneous mixture or solution due to the presence of hydrocarbons. These attract one another, forming spherical aggregates called micelles. The lipophilic "tails" of the hydrocarbons are turned toward the interior of the micelle, while the hydrophilic heads remain facing toward the water that forms the external phase.

## ALLOYS

We have primarily discussed liquid mixtures, but in fact mixtures can be gaseous or even solid—as for example in the case of an alloy, a mixture of two or more metals. Alloys are usually created by melting the component metals, then mixing them together in specific proportions, but an alloy can also be created by bonding metal powders.

The structure of an elemental metal includes tight "electron sea" bonds, which are discussed in the essay on Metals. These, combined with the

## KEY TERMS

**ALLOY:** A mixture of two or more metals.

**AQUEOUS:** A term describing a solution in which a substance or substances are dissolved in water.

**ATOM:** The smallest particle of an element.

**CHEMICAL SPECIES:** A generic term used for any substance studied in chemistry—whether it be an element, compound, mixture, atom, molecule, ion, and so forth.

**COMPOUND:** A substance made up of atoms of more than one element, which are chemically bonded and usually joined in molecules. The composition of a compound is always the same, unless it is changed chemically.

**DISPERSION:** A term describing the distribution of particles in a fluid.

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

**EMULSIFIER:** A surfactant.

**EMULSION:** A mixture of two immiscible liquids such as oil and water, made by dispersing microscopic droplets of one liquid in another. In creating an emulsion, surfactants act as bridges between the two liquids.

**FLUID:** A substance with the ability to flow. In physical sciences such as chemistry and physics, "fluid" refers both to liquids and gases.

**HETEROGENEOUS:** A term describing a mixture that is not the same throughout; rather, it has various regions possessing different properties. An example of a mixture is sand in a container of water. Rather than dissolving to form a homogeneous mixture, as sugar would, the sand sinks to the bottom.

**HOMOGENEOUS:** A term describing a mixture that is the same throughout, as for example when sugar is fully dissolved in water. A solution is a homogenous mixture.

**IMMISCIBLE:** Possessing a negligible value of miscibility.

**ION:** An atom or group of atoms that has lost or gained one or more electrons, and thus has a net electric charge.

**MISCIBILITY:** A qualitative term identifying the relative ability of two substances to dissolve in one another.

**MIXTURE:** A substance with a variable composition, meaning that it is composed of molecules or atoms of differing types. Compare with pure substance or compound.

**MOLECULE:** A group of atoms, usually but not always representing more than one element, joined in a structure. Compounds are typically made of up molecules.

**PHENOMENOLOGICAL:** A term describing scientific definitions based purely on experimental phenomena. These only convey part of the picture, however—primarily, the part a chemist can perceive either through measurement or through the senses, such as sight. A structural definition is therefore usually preferable to a phenomenological one.

## KEY TERMS CONTINUED

**PURE SUBSTANCE:** A substance that has the same composition throughout. Pure substances are either elements or compounds, and should not be confused with mixtures. A homogeneous mixture is not the same as a pure substance, because although it has an unvarying composition, it cannot be reduced to a single type of atom or molecule.

**SOLUTION:** A homogeneous mixture in which one or more substances is dissolved in another substances—for example, sugar dissolved in water.

**STRUCTURAL:** A term describing scientific definitions based on aspects of molecular structure rather than purely phenomenological data.

**SURFACTANT:** A substance made up of molecules that are both water- and oil-soluble, which acts as an agent for joining other substances in an emulsion.

**SUSPENSION:** A term that refers to a mixture in which solid particles are suspended in a fluid.

metal's crystalline structure, create a situation in which internal bonding is very strong, but nondirectional. As a result, most metals form alloys, but again, this is not the same as a compound: the elemental metals retain their identity in these metal composites, forming characteristic fibers, beads, and other shapes.

**SOME FAMOUS ALLOYS.** One of the most important alloys in early human history was a 25:75 mixture of tin and copper that gave its name to an entire stage of technological development: the Bronze Age (c. 3300-1200 B.C.). This combination formed a metal much stronger than either copper or tin, and bronze remained dominant until the discovery of new iron-smelting methods ushered in the Iron Age in about 1200 B.C.

Another important alloy of the ancient world was brass, which is about one-third zinc to two-thirds copper. Introduced in the period c. 1400-c. 1200 B.C, brass was one of the metals that defined the world in which the Bible was written. Biblical references to it abound, as in the famous passage from I Corinthians 13 (read at many weddings), in which the Apostle Paul proclaims that "without love, I am as sounding brass." Some biblical scholars, however, maintain that some of the references to brass in the Old Testament are actually mistranslations of "bronze."

Tin, copper, and antimony form pewter, a soft mixture that can be molded when cold and beaten regularly without turning brittle. Though used in Roman times, it became most popular in England from the fourteenth to the eighteenth centuries, when it offered a cheap substitute for silver in plates, cups, candelabra, and pitchers. The pewter turned out by colonial American metalsmiths is still admired for its beauty and functionality.

As for iron, it appears in nature as an impure ore, but even when purified, it is typically alloyed with other elements. Among the well-known forms of iron are cast iron, a variety of mixtures containing carbon and/or silicon; wrought iron, which contains small amounts of various other elements, such as nickel, cobalt, copper, chromium, and molybdenum; and steel. Steel is a mixture of iron with manganese and chromium, purified with a blast of hot air. Steel is also sometimes alloyed with aluminum in a one-third/two-thirds mixture to make duraluminum, developed for the superstructures of German zeppelins during World War I.

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# SOLUTIONS

## CONCEPT

We are most accustomed to thinking of solutions as mixtures of a substance dissolved in water, but in fact the meaning of the term is broader than that. Certainly there is a special place in chemistry for solutions in which water—"the universal solvent"—provides the solvent medium. This is also true in daily life. Coffee, tea, soft drinks, and even water itself (since it seldom appears in pure form) are solutions, but the meaning of the term is not limited to solutions involving water. Indeed, solutions do not have to be liquid; they can be gaseous or solid as well. One of the most important solutions in the world, in fact, is the air we breathe, a combination of nitrogen, oxygen, noble gases, carbon dioxide, and water vapor. Nonetheless, aqueous or water-based substances are the focal point of study where solutions are concerned, and reactions that take place in an aqueous solution provide an important area of study.

## HOW IT WORKS

### Mixtures

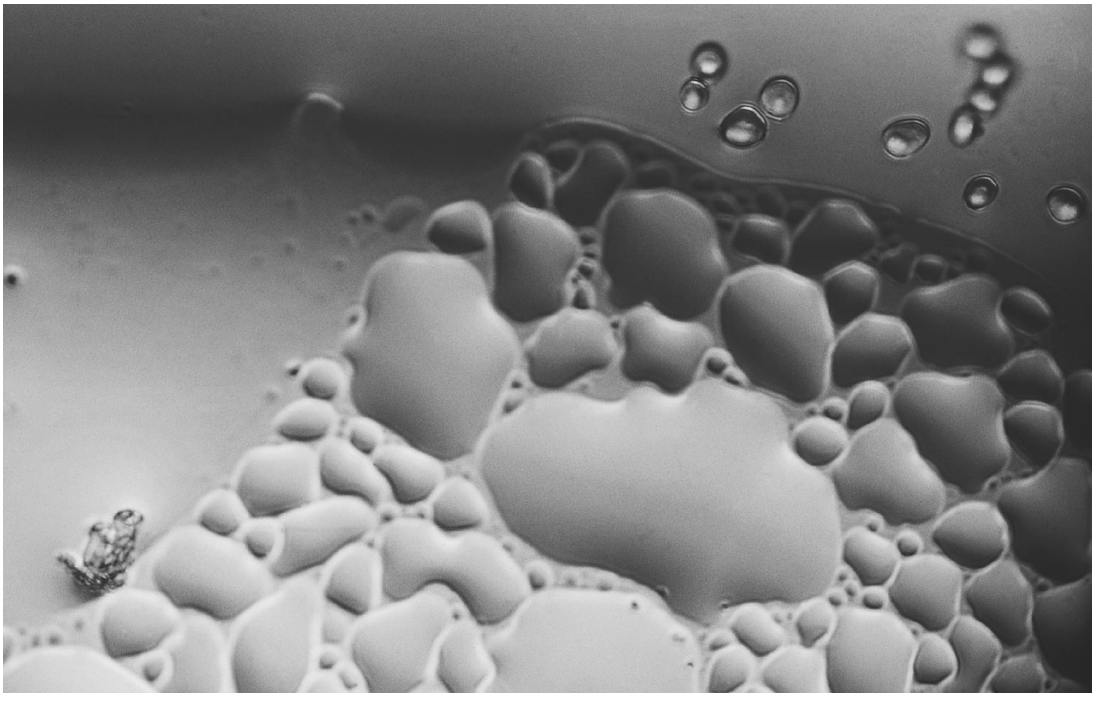
Solutions belong to the category of substances identified as mixtures, substances with variable composition. This may seem a bit confusing, since among the defining characteristics of a solution are its uniformity and consistency. But this definition of a solution involves external qualities—the things we can observe with our senses—whereas a mixture can be distinguished from a pure substance not only in terms of external characteristics, but also because of its internal and structural properties.

At one time, chemists had a hard time differentiating between mixtures and pure substances (which are either elements or compounds), primarily because they had little or no knowledge of those "internal and structural properties." Externally, a mixture and compound can be difficult to distinguish, but the "variable composition" mentioned above is a key factor. Coffee can be almost as weak as water, or so strong it seems to galvanize the throat as it goes down—yet in both cases, though its composition has varied, it is still coffee.

By contrast, if a compound is altered by the variation of just one atom in its molecular structure, it becomes something else entirely. When an oxygen atom bonds with a carbon and oxygen atom, carbon monoxide—a poisonous gas produced by the burning of fossil fuels—is turned into carbon dioxide, an essential component of the interaction between plants and animals in the natural environment.

**MIXTURES VS. COMPOUNDS: THREE DISTINCTIONS.** Air (a mixture) can be distinguished from a compound, such as carbon dioxide, in three ways. First, a mixture can exist in virtually any proportions among its constituent parts, whereas a compound has a definite and constant composition. Air can be oxygen-rich or oxygen-poor, but if we vary the numbers of oxygen atoms chemically bonded to form a compound, the result is an entirely different substance.

Second, the parts of a mixture retain most of their properties when they join together, but elements—once they form a compound—lose their elemental characteristics. If pieces of carbon were floating in the air, their character would be quite



Water and oil droplets exposed to polarized light. Water and oil have very little miscibility with regard to one another, meaning that they tend to remain separate when combined. *(Science Pictures Limited/Corbis. Reproduced by permission.)*

different from that of the carbon in carbon dioxide. Carbon, in its natural form, is much like coal or graphite (graphite is pure carbon, and coal an impure form of the element), but when a carbon atom combines with an oxygen atom, the two form a gas. Pieces of carbon in the air, on the other hand, would be solid, as carbon itself is.

Third, a mixture can usually be created simply by the physical act of stirring items together, and/or by applying heat. Certainly this is true of many solutions, such as brewed coffee. On the other hand, a compound such as carbon dioxide can only be formed by the chemical reaction of atoms in specific proportions and at specific temperatures. Some such reactions consume heat, whereas others produce it. These interactions of heat are highly complex; on the other hand, in making coffee, heat is simply produced by an external source (the coffee maker) and transferred to the coffee in the brewing process.

**HETEROGENEOUS AND HOMOGENEOUS MIXTURES.** There are two basic types of mixtures. One of these occurs, for instance, when sand is added to a beaker of water: the sand sinks to the bottom, and the composition of the sand-water mixture cannot be said to be the same throughout. It is thus a heterogeneous mixture. The same is true of cold tea when table sugar (sucrose) is added to it: the sugar drifts to the bottom, and as a result, the first sip of tea from the glass is not nearly as sweet as the last.

Wood is a mixture that typically appears in heterogeneous form, a fact that can be easily confirmed by studying wood paneling. There are knots, for instance—areas where branches once grew, and where the concentrations of sap are higher. Striations of color run through the boards of paneling, indicating complex variations in the composition of the wood. Much the same is true of soil, with a given sample varying widely depending on a huge array of factors: the concentrations of sand, rock, or decayed vegetation, for instance, or the activities of earthworms and other organisms in processing the soil.

In a homogeneous mixture, by contrast, there is no difference between one area of the mixture and another. If coffee has been brewed properly, and there are no grounds at the bottom of the pot, it is homogeneous. If sweetener is added to tea while it is hot, it too should yield a homogeneous mixture.



Water and ethanol are completely miscible, whether the solution be 99% water and 1% ethanol, 50% of both, or 99% ethanol and 1% water. Shown here is a glass of beer—an example of a water-ethanol solution. *(Owen Franken/Corbis. Reproduced by permission.)*

## Solutions and Solubility

Virtually all varieties of homogeneous mixtures can be classified as a solution—that is, a homogeneous mixture in which one or more substances is dissolved in another substance. If two or more substances were combined in exactly equal proportions, this would technically not be a solution; hence the distinction between solutions and the larger class of homogeneous mixtures.

A solution is made up of two parts: the solute, the substance or substances that are dissolved; and the solvent, the substance that dissolves the solute. The solvent typically determines the physical state of the solution: in other words, if the solvent is a liquid, the solution will most likely be a liquid. Likewise if the solvent is a solid such as a metal, melted at high temperatures to form a metallic solution called an alloy, then when the solution is cooled to its normal temperature, it will be solid again.

**Miscibility and solubility.** Miscibility is a term describing the relative ability of two substances to dissolve in one another. Generally, water and water-based substances have high miscibility with regard to one another, as do oil and oil-based substances. Oil and water, on the other hand (or substances based in either) have very low miscibility. The reasons for this will be discussed below.

Miscibility is a qualitative term like "fast" or "slow"; on the other hand, solubility—the maximum amount of a substance that dissolves in a given amount of solvent at a specific temperature—can be either qualitative or quantitative. In a general sense, the word is qualitative, referring to the property of being soluble, or able to dissolve in a solution.

At some points in this essay, "solubility" will be used in this qualitative sense; however, within the realm of chemistry, it also has a quantitative meaning. In other words, instead of involving an imprecise quality such as "fast" or "slow," solubility in this sense relates to precise quantities more along the lines of "100 MPH (160.9 km/h)." Solubility is usually expressed in grams (g) (0.0022 lb) of solute per 100 g (0.22 lb) of solvent.

**Other quantitative terms.** Another quantitative means of describing a solution is in terms of mass percent: the mass of the solute divided by the mass of the solution, and multiplied by 100%. If there are 25 g of solute in a solution of 200 g, for instance, 25 would be divided by 200 and multiplied by 100% to yield a 12.5% figure of solution composition.

Molarity also provides a quantitative means of showing the concentration of solute to solution. Whereas mass percent is, as its name indicates, a comparison of the mass of the solute to that of the solvent, molarity shows the amount of solute in a given volume of solution. This is measured in moles of solute per liter of solution, abbreviated mol/l.

# Real-Life Applications

## Saturation and Dilution

The quantitative terms for describing solubility that we have reviewed are useful to a professional chemist, or to anyone performing work in a laboratory. For the most part, however, qualita-

tive expressions will suffice for the present discussion. Among the most useful qualitative terms is saturation.

When it is possible to dissolve solute in a solvent, the solution is said to be unsaturated—rather like a sponge that has not been filled to capacity with liquid. By contrast, a solution that contains as much solute as it can at a given temperature is like a sponge that has been filled with all the liquid it can possibly contain. It can no longer absorb more of the liquid; rather, it can only push liquid particles along, and the sponge is said to be saturated. In the same way, if tea is hot, it is easier to introduce sugar to it, but when the temperature is low, sugar will not dissolve as easily.

**Saturation and temperature.** With tea and many other substances, higher temperatures mean that a greater amount of solute can be added before the solution is fully saturated. The reason for this relationship between saturation and temperature, according to generally accepted theory, is that heated solvent particles move more quickly than cold ones, and as a result, create more space into which the solvent can fit. Indeed, "space" is a prerequisite for a solution: the molecules of solute need to find a "hole" between the molecules of solvent into which they can fit. Thus the molecules in a solution can be compared to a packed crowd: if a crowd is suddenly dispersed, it is easier to walk through it.

Not all substances respond to rises in temperature in the manner described, however. As a rule, gases (with the exception of helium) are more soluble at lower temperatures than at higher ones. Higher temperatures mean an increase in kinetic energy, with more molecules colliding with one another, and this makes it easier for the gases to escape the liquid in which they are dissolved.

Carbonated soft drinks get their "fizz" from carbon dioxide gas dissolved, along with sugar and other flavorings, in a solution of water. When the soft-drink container is opened, much of the carbon dioxide quickly departs, while a certain proportion stays dissolved in the cola. The remaining carbon dioxide will eventually escape as well, but it will do so more quickly if left in a warm environment rather than a cold one, such as the inside of a refrigerator.

**Dilution and concentration.** Another useful set of qualitative terms for solutions also relates to the relative amount of solute that has been dissolved. But whereas saturation is an absolute condition at a certain temperature (in other words, the solution is definitely saturated at such-and-such a temperature), concentration and dilution are much more relative terms.

When a solution contains a relatively small amount of solute, it is said to be dilute; on the other hand, a solution with a relatively large amount of solute is said to be concentrated. For instance, hydrogen peroxide ($H_2O_2$) as sold over the counter in drug stores, to be used in homes as a disinfectant of bleaching agent, is a dilute 3% solution in water. In higher concentrations, hydrogen peroxide can cause burns to human skin, and is used to power rockets.

Chemists often keep on hand in their laboratories concentrated versions of various frequently used solutions. Maintaining them in concentrated form saves space; when more of a solution is needed, the chemist dilutes it in water according to desired molarity values. To do so, the chemist determines how much water needs to be added to a particular "stock solution" (as these concentrated solutions in a laboratory are called) to create a solution of a particular concentration. In the dilution with water, the number of moles of the solute does not change; rather, the particles of solute are dispersed over a larger volume.

## "Like Dissolves Like"

In the molecules of a compound, the atoms are held together by powerful attractions. The molecules within a compound, however, also have an intermolecular attraction, but this is much weaker than the interatomic bonds in a molecule. It is thus quite possible for the molecules in a solution to exert a greater attractive force than the one holding the molecules of solute together with one another. When this happens, the solute dissolves.

A useful rule of thumb when studying solutions is "like dissolves like." In other words, water dissolves water-based solutes, whereas oil dissolves oily substances. Or to put it another way, water and water-based substances are miscible with one another, as are oil and oil-based substances. Water and oil together, however, are largely immiscible.

**POLAR WATER, NONPOLAR OIL.** Water and oil and immiscible due to their respective molecule structures, and hence their inherent characteristics of intermolecular bonding. Water molecules are polar, meaning that the positive electric charge is at one end of the molecule, while the negative charge is at the other end. Oil, on the other hand, is nonpolar—charges are more evenly distributed throughout the molecule.

The oxygen atom in a water molecule has a much greater electronegativity than the hydrogen atoms, so it pulls negatively charged electrons to its end of the molecule. Conversely, most oils are composed of carbon and hydrogen, which have similar values of electronegativity. As a result, positive and negative charges are distributed evenly throughout the oil molecule. Whereas a water molecule is like a magnet with a north and south pole, an oil molecule is like a nonmagnetic metal. Thus, as most people know, "oil and water don't mix."

The immiscible quality of oil and water in relation to one another explains a number of phenomena from the everyday world. It is easy enough to wash mud from your hands under running water, because the water and the mud (which, of course, contains water) are highly miscible. But motor oil or oil-based paint will leave a film on the hands, as these substances bond to oily molecules in the skin itself, and no amount of water will wash the film off. To remove it, one needs mineral spirits, paint thinner, or soap manufactured to bond with the oils.

Everyone has had the experience of eating spicy foods and then trying to cool down the mouth with cold water—and just about everyone has discovered that this does not work. This is because most spicy substances contain emulsified oils that coat the tongue, and these oils are not attracted to water. A much better "solution" (in more ways than one) is milk, and in particular, whole milk. Though a great deal of milk is composed of water, it also contains tiny droplets of fats and proteins that join with the oils in spicy substances, thus cooling down the mouth.

## Crossing the Oil/Water Barrier

The active ingredient in a dry-cleaning chemical usually has nonpolar molecules, because the toughest stains are made by oils and greases. But what about ordinary soap, which we use in water to wash both water- and oil-based substances from our bodies? Though, as noted earlier, certain kinds of oil stains require special cleaning solutions, ordinary soap is fine for washing off the natural oils secreted by the skin. Likewise, it can wash off small concentrations of oil that come from the environment and attach to the skin—for instance, from working over a deep fryer in a fast-food restaurant.

How does the soap manage to "connect" both with oils and water? Likewise, how does milk—which is water-soluble and capable of dilution in water—wash away the oils associated with spicy food? To answer these questions, we need to briefly consider a subject examined in more depth within the Mixtures essay: emulsions, or mixtures of two immiscible liquids.

**EMULSIFIERS AND SURFACTANTS.** The dispersion of two substances in an emulsion is achieved through the use of an emulsifier or surfactant. Made up of molecules that are both water- and oil-soluble, an emulsifier or surfactant acts as an agent for joining other substances in an emulsion. The two words are virtually synonymous, but "emulsifier" is used typically in reference to foods, whereas "surfactant" most often refers to an ingredient in detergents and related products.

In an emulsion, millions of surfactants surround the dispersed droplets of solute, known as the internal phase, shielding them from the solvent, or external phase. Surfactants themselves are often used in laundry or dish detergent, because most stains on plates or clothes are oil-based, whereas the detergent itself is applied to the clothes in a water-based external phase. The emulsifiers in milk help to bond oily particles of milk fat (cream) and protein to the external phase of water that comprises the majority of milk's volume.

As for soap, it is a mixture of an acid and a base—specifically, carboxylic acids joined with a base such as sodium hydroxide. Carboxylic acids, chains of hydrogen and carbon atoms, are just some of many hydrocarbons that form the chemical backbone of a vast array of organic substances. Because it is a salt, meaning that it is formed from the reaction of an acid with a base, soap partially separates into its component ions in water. The active ion is RCOO- (R stands for

the hydrocarbon chain), whose two ends behave in different fashions, making it a surfactant.

The hydrocarbon end (R-) is said to be lipophilic, or "oil-loving"; on the other hand, the carboxylate end (-COO-) is hydrophilic, or "water-loving." As a result, soap can dissolve in water, but can also clean greasy stains. When soap is mixed with water, it does not form a true solution, due to the presence of the hydrocarbons, which attract one another to form spherical aggregates called micelles. The lipophilic "tails" of the hydrocarbons are turned toward the interior of the micelle, while the hydrophilic "heads" remain facing toward the water that forms the external phase.

**ETHANOL.** When a hydrocarbon joins with other substances in one of the hydrocarbon functional groups, these form numerous hydrocarbon derivatives. Among the hydrocarbon derivatives is alcohol, and within this grouping is ethyl alcohol or ethanol, which includes a hydrocarbon bonded to the –OH functional group. The formula for ethanol is $C_2H_6O$, though this is sometimes rendered as $C_2H_5OH$ to show that the alcohol functional group (–OH) is bonded to the hydroxyl radical ($C_2H_5$).

Ethanol, the same alcohol found in alcoholic beverages, is obviously miscible with water. Beer, after all, is mostly water, and if ethanol and water were not miscible, it would be impossible to mix alcohol with water or a water-based substance to make Scotch and water or a Bloody Mary (vodka and tomato juice.) In fact, water and ethanol are completely miscible, whether the solution be 99% water and 1% ethanol, 50% of both, or 99% ethanol and 1% water.

How can this be, given the fact that ethanol is a hydrocarbon derivative—in other words, a cousin of petroleum? The addition of the term "derivative" gives us a clue: note that ethanol contains oxygen, just as water does. As in water, the oxygen and hydrogen form a polar bond, giving that portion of the ethanol molecule a high affinity for water. Molecules of water and the alcohol functional group are joined through an intermolecular force called hydrogen bonding.

## Aqueous Solutions

The term aqueous refers to water, and because water has extraordinary solvent qualities (discussed in the Osmosis essay) it serves as the medium for numerous solutions. Furthermore, reactions in aqueous solutions—though we can only touch on them briefly here—constitute a large and significant body of reactions studied by chemists.

Most of the solutions we have discussed up to this point are aqueous. We have referred, at least in an external or phenomenological way, to the means by which sugar dissolves in an aqueous solution, such as tea. Now let us consider, from a molecular or structural standpoint, the means by which salt does so as well.

**SALTWATER.** Salt is formed of positively charged sodium ions, firmly bonded to negatively charged chlorine ions. To break these ionic bonds and dissolve the sodium chloride, water must exert a strong attraction. However, salt is not really composed of molecules but simply repeating series of sodium and chlorine atoms joined together in a simple face-centered cubic lattice which has each each sodium ion ($Na^+$) surrounded by six chlorine ions ($Cl^-$); at the same time, each chlorine ion is surrounded by six sodium ions.

In dissolving the salt, water molecules surround ions that make up the salt, holding them in place through the electrical attraction of opposite charges. Due to the differences in electronegativity that give the water molecule its high polarity, the hydrogen atoms are more positively charged, and thus these attract the negatively charged chlorine ion. Similarly, the negatively charged oxygen end of the water molecule attracts the positively charged sodium ion. As a result, the salt is "surrounded" or dissolved.

**PLASMA AND AQUEOUS-SOLUTION REACTIONS IN THE BODY.** Whereas saltwater is an aqueous solution that can eventually kill someone who drinks it, plasma is an essential component of the life process—and in fact, it contains a small quantity of sodium chloride. Not to be confused with the phase of matter also called plasma, this plasma is the liquid portion of blood. Blood itself is about 55% plasma, with red and white blood cells and platelets suspended in it.

Plasma is in turn approximately 90% water, with a variety of other substances suspended or dissolved in it. Prominent among these substances are proteins, of which there are about 60 in plasma, and these serve numerous important functions—for instance, as antibodies. Plasma

## KEY TERMS

**AQUEOUS:** A term describing a solution in which a substance or substances are dissolved in water.

**COMPOUND:** A substance made up of atoms of more than one element, which are chemically bonded and usually joined in molecules. The composition of a compound is always the same, unless it is changed chemically.

**CONCENTRATED:** A qualitative term describing a solution with a relatively large ratio of solute to solvent.

**DILUTE:** A qualitative term describing a solution with a relatively small ratio of solute to solvent.

**EMULSIFIER:** A surfactant. (Usually the term "emulsifier" is applied to foods, and "surfactant" to detergents and other inedible products.)

**EMULSION:** A mixture of two immiscible liquids, such as oil and water, made by dispersing microscopic droplets of one liquid in another. In creating an emulsion, surfactants act as bridges between the two liquids.

**HETEROGENEOUS:** A term describing a mixture that is not the same throughout; rather, it has various regions possessing different properties. One example of this is sand in a container of water. Rather than dissolving to form a homogeneous mixture as sugar does, the sand sinks to the bottom.

**HOMOGENEOUS:** A term describing a mixture that is the same throughout, as for example when sugar is fully dissolved in water. A solution is a homogenous mixture.

**IMMISCIBLE:** Possessing a negligible value of miscibility.

**MASS PERCENT:** A quantitative means of measuring solubility in terms of the mass of the solute divided by the mass of the solution, multiplied by 100%.

**MISCIBILITY:** A term identifying the relative ability of two substances to dissolve in one another. Miscibility is qualitative, like "fast" or "slow"; solubility, on the other hand, can be a quantitative term.

**MIXTURE:** A substance with a variable composition, composed of molecules or atoms of differing types. Compare with pure substance.

also contains ions, which prevent red blood cells from taking up excess water in osmosis. Prominent among these ions are those of salt, or sodium chloride. Plasma also transports nutrients such as amino acids, glucose, and fatty acids, as well as waste products such as urea and uric acid, which it passes on to the kidneys for excretion.

Much of the activity that sustains life in the body of a living organism can be characterized as a chemical reaction in an aqueous solution. When we breathe in oxygen, it is taken to the lungs and fed into the bloodstream, where it associates with the iron-containing hemoglobin in red blood cells and is transported to the organs. In the stomach, various aqueous-solution reactions process food, turning part of it into fuel that the blood carries to the cells, where the oxygen engages in complex reactions with nutrients.

### A Miscellany of Solutions

Aqueous-solution reactions can lead to the formation of a solid, as when a solution of potassi-

## KEY TERMS CONTINUED

**MOLARITY:** A quantitative means of showing the concentration of solute to solution. This is measured in moles of solute per liter of solution, abbreviated mol/L.

**PURE SUBSTANCE:** A substance—either an element or compound—that has an unvarying composition. This means that by changing the proportions of atoms, the result would be an entirely different substance. Compare with mixture.

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

**QUANTITATIVE:** Involving a comparison between precise quantities—for instance, 10 lb vs. 100 lb, or 50 MPH vs. 120 MPH.

**SATURATED:** A qualitative term describing a solution that contains as much solute as it can dissolve at a given temperature.

**SOLUBILITY:** In a broad, qualitative sense, solubility refers to the property of being soluble. Chemists, however, usually apply the word in a quantitative sense, to indicate the maximum amount of a substance that dissolves in a given amount of solvent at a specific temperature. Solubility is usually expressed in grams of solute per 100 g of solvent.

**SOLUBLE:** Capable of dissolving in a solvent.

**SOLUTE:** The substance or substances that are dissolved in a solvent to form a solution.

**SOLUTION:** A homogeneous mixture in which one or more substances (the solute) is dissolved in a solvent—for example, sugar dissolved in water.

**SOLVENT:** The substance or substances that dissolve a solute to form a solution.

**SURFACTANT:** A substance made up of molecules that are both water- and oil-soluble, which acts as an agent for joining other substances in an emulsion.

**UNSATURATED:** A term describing a solution that is capable of dissolving additional solute, if that solute is introduced to it.

um chromate ($K_2CrO_4$) is added to an aqueous solution of barium nitrate ($Ba[NO_3]_2$ to form solid barium chromate ($BaCrO_4$) and a solution of potassium nitrate ($KNO_3$). This reaction is described in the essay on Chemical Reactions.

We have primarily discussed liquid solutions, and in particular aqueous solutions. It should be stressed, however, that solutions can also exist in the gaseous or solid phases. The air we breathe is a solution, not a compound: in other words, there is no such thing as an "air molecule." Instead, it is made up of diatomic elements (those in which two atoms join to form a molecule of a single element); monatomic elements (those elements that exist as single atoms); one element in a triatomic molecule; and two compounds.

The "solvent" in air is nitrogen, a diatomic element that accounts for 78% of Earth's atmosphere. Oxygen, also diatomic, constitutes an additional 21%. Argon, which like all noble gases is monatomic, ranks a distant third, with 0.93%. The remaining 0.07% is made up of traces of other noble gases; the two compounds men-

tioned, carbon dioxide and water (in vapor form); and, high in the atmosphere, the triatomic form of oxygen known as ozone ($O_3$).

The most significant solid solutions are alloys of metals, discussed in the essay on Mixtures, as well as in essays on various metal families, particularly the Transition Metals. Some well-known alloys include bronze (three-quarters copper, one-quarter tin); brass (two-thirds copper, one-third zinc); pewter (a mixture of tin and copper with traces of antimony); and numerous alloys of iron—particularly steel—as well as alloys involving other metals.

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# OSMOSIS

## CONCEPT

The term osmosis describes the movement of a solvent through a semipermeable membrane from a less concentrated solution to a more concentrated one. Water is sometimes called "the perfect solvent," and living tissue (for example, a human being's cell walls) is the best example of a semipermeable membrane. Osmosis has a number of life-preserving functions: it assists plants in receiving water, it helps in the preservation of fruit and meat, and is even used in kidney dialysis. In addition, osmosis can be reversed to remove salt and other impurities from water.

## HOW IT WORKS

If you were to insert a hollow tube of a certain diameter into a beaker of water, the water would rise inside the tube and reach the same level as the water outside it. But suppose you sealed the bottom end of the tube with a semipermeable membrane, then half-filled the tube with salt water and again inserted it into the beaker. Over a period of time, the relative levels of the salt water in the tube and the regular water in the beaker would change, with the fresh water gradually rising into the beaker.

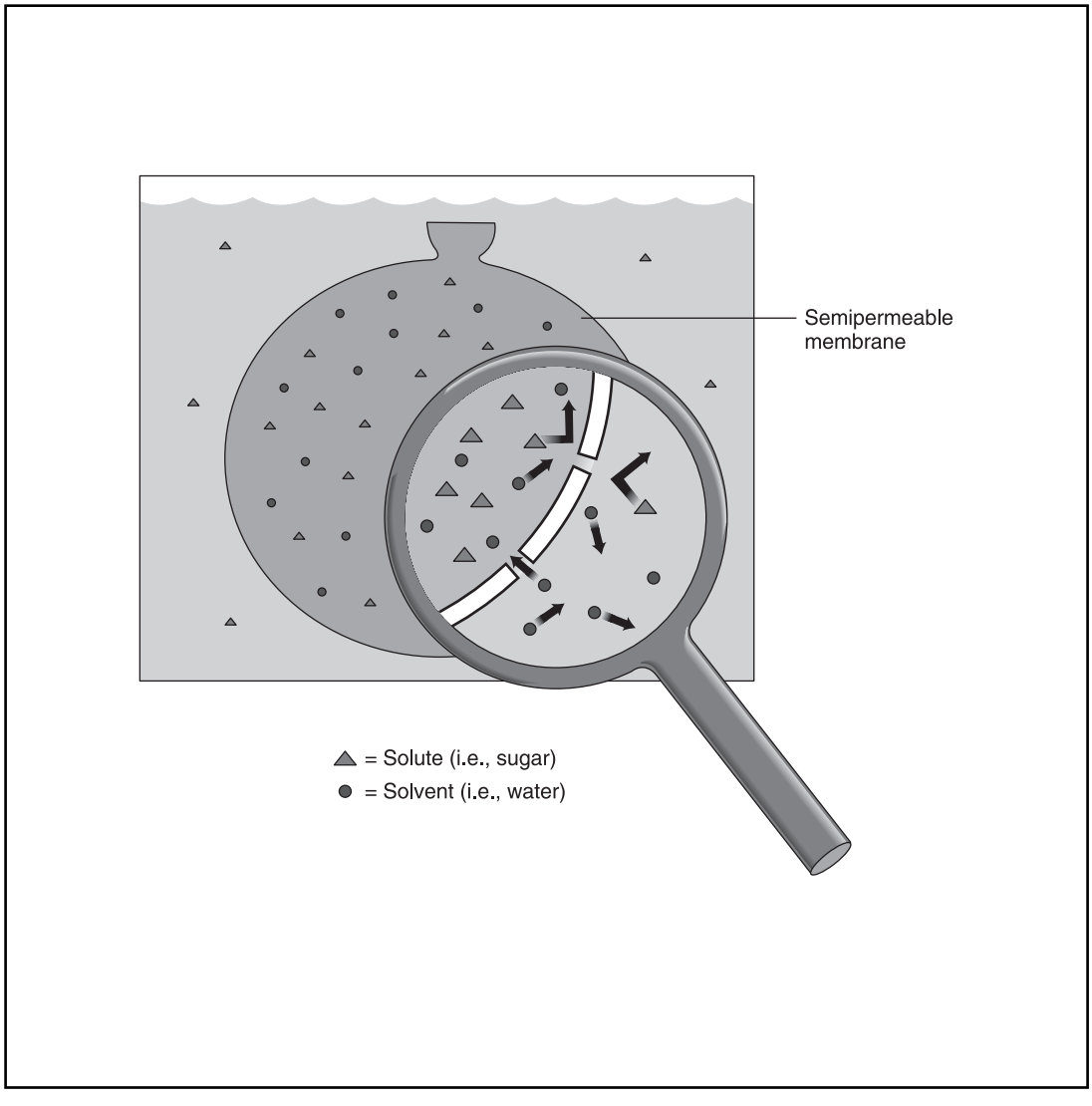
This is osmosis at work; however, before investigating the process, it is necessary to understand at least three terms. A solvent is a liquid capable of dissolving or dispersing one or more other substances. A solute is the substance that is dissolved, and a solution is the resulting mixture of solvent and solute. Hence, when you mix a packet of sugar into a cup of hot coffee, the coffee—which is mostly water—acts as a solvent for the sugar, a solute, and the resulting sweetened coffee is a solution. (Indeed, people who need a cup of coffee in the morning might say that it is a "solution" in more ways than one!) The relative amount of solute in the solution determines whether it can be described as more or less concentrated.

### Water and Oil: Molecular Differences

In the illustrations involving the beaker and the hollow tube, water plays one of its leading roles, as a solvent. It is possible to use a number of other solvents for osmosis, but most of the ones that will be discussed here are water-based substances. In fact, virtually everything people drink is either made with water as its central component (soft drinks, coffee, tea, beer and spirits), or comes from a water-based plant or animal life form (fruit juices, wine, milk.) Then of course there is water itself, still the world's most popular drink.

By contrast, people are likely to drink an oily product only in extreme circumstances: for instance, to relieve constipation, holistic-health practitioners often recommend a mixture of olive oil and other compounds for this purpose. Oil, unlike water, has a tendency to pass straight through a person's system, without large amounts of it being absorbed through osmosis. In fact, oil and water differ significantly at the molecular level.

Water is the best example of a polar molecule, sometimes called a dipole. As everyone knows, water is a name for the chemical $H_2O$, in which two relatively small hydrogen atoms bond with a large atom of oxygen. You can visualize a water molecule by imagining oxygen as a basketball with hydrogen as two baseballs fused to the



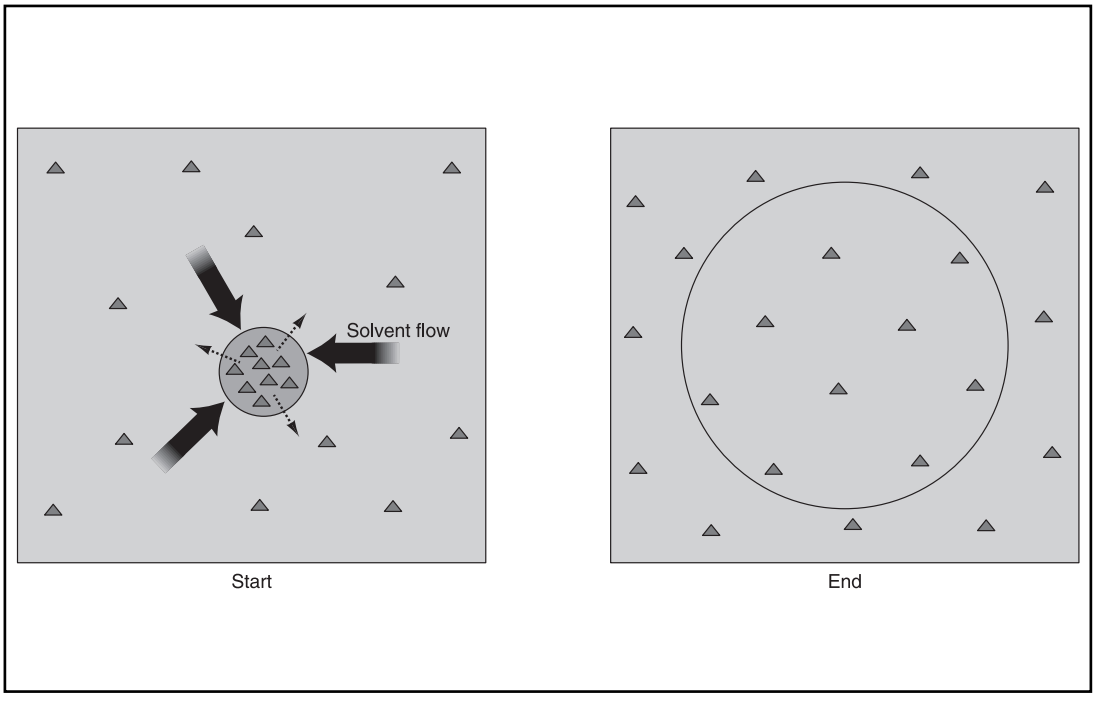

A semipermeable membrane permits only certain components of solutions, usually the solvent, to pass through.

basketball's surface. Bonded together as they are, the oxygen tends to pull electrons from the hydrogen atoms, giving it a slight negative charge and the hydrogen a slight positive charge.

As a result, one end of a water molecule has a positive electrical charge, and the other end a negative charge. This in turn causes the positive end of one molecule to attract the negative side of its neighbor, and vice versa. Though the electromagnetic force is weak, even in relative terms, it is enough to bond water molecules tightly to one another.

By contrast, oily substances—whether the oil is animal-, vegetable-, or petroleum-based—are typically nonpolar, meaning that the positive and negative charges are distributed evenly across the surface of the molecule. Hence, the bond between oil molecules is much less tight than for water molecules. Clean motor oil in a car's crankshaft behaves as though it were made of millions of tiny ball-bearings, each rolling through the engine without sticking. Water, on the other hand, has a tendency to stick to surfaces, since its molecules are so tightly bonded to one another.

This tight bond gives water highly unusual properties compared to other substances close to its molecular weight. Among these are its high boiling point, its surprisingly low density when frozen, and the characteristics that make osmosis possible. Thanks to its intermolecular structure, water is not only an ideal solvent, but its closely




Osmosis equalizes concentration.

packed structure enables easy movement, as, for instance, from an area of low concentration to an area of high concentration.

In the beaker illustration, the "pure" water is almost pure solvent. (Actually, because of its solvent qualities, water seldom appears in a pure state unless one distills it: even water flowing through a "pure" mountain stream carries all sorts of impurities, including microscopic particles of the rocks over which it flows.) In any case, the fact that the water in the beaker is almost pure makes it easy for it to flow through the semipermeable membrane in the bottom of the tube. By contrast, the solute particles in the salt-water solution have a much harder time passing through, and are much more likely to block the openings in the membrane. As a result, the movement is all in one direction: water in the beaker moves through the membrane, and into the tube.

A few points of clarification are in order here. A semipermeable membrane is anything with a structure somewhere between that of, say, plastic on the one hand and cotton on the other. Were the tube in the beaker covered with Saran wrap, for instance, no water would pass through. On the other hand, if one used a piece of cotton in the bottom of the tube, the water would pass straight through without osmosis taking place. In contrast to cotton, Gore-tex is a fabric containing a very thin layer of plastic with billions of tiny pores which let water vapor flow out without allowing liquid water to seep in. This accounts for the popularity of Gore-tex for outdoor gear—it keeps a person dry without holding in their sweat. So Gore-tex would work well as a semipermeable membrane.

Also, it is important to consider the possibilities of what can happen during the process of osmosis. If the tube were filled with pure salt, or salt with only a little water in it, osmosis would reach a point and then stop due to osmotic pressure within the substance. Osmotic pressure results when a relatively concentrated substance takes in a solvent, thus increasing its pressure until it reaches a point at which the solution will not allow any more solvent to enter.

## REAL-LIFE APPLICATIONS

### Cell Behavior and Salt Water

Cells in the human body and in the bodies of all living things behave like microscopic bags of solution housed in a semipermeable membrane. The health and indeed the very survival of a person, animal, or plant depends on the ability of



In this 1966 photo, a girl is undergoing kidney dialysis, a crucial modern medical application that relies on osmosis. *(Bettmann/Corbis. Reproduced by permission.)*

the cells to maintain their concentration of solutes.

Two illustrations involving salt water demonstrate how osmosis can produce disastrous effects in living things. If you put a carrot in salty water, the salt water will "draw" the water from inside the carrot—which, like the human body and most other forms of life, is mostly made up of water. Within a few hours, the carrot will be limp, its cells shriveled.

Worse still is the process that occurs when a person drinks salt water. The body can handle a little bit, but if you were to consume nothing but salt water for a period of a few days, as in the case of being stranded on the proverbial desert island, the osmotic pressure would begin drawing water from other parts of your body. Since a human body ranges from 60% water (in an adult male) to 85% in a baby, there would be a great deal of water available—but just as clearly, water is the essential ingredient in the human body. If you continued to ingest salt water, you would eventually experience dehydration and die.

How, then, do fish and other forms of marine life survive in a salt-water environment? In most cases, a creature whose natural habitat is the ocean has a much higher solute concentration in its cells than does a land animal. Hence, for them, salt water is an isotonic solution, or one that has the same concentration of solute—and hence the same osmotic pressure—as in their own cells.

## Osmosis in Plants

Plants depend on osmosis to move water from their roots to their leaves. The further toward the edge or the top of the plant, the greater the solute concentration, which creates a difference in osmotic pressure. This is known as osmotic potential, which draws water upward. In addition, osmosis protects leaves against losing water through evaporation.

Crucial to the operation of osmosis in plants are "guard cells," specialized cells dispersed along the surface of the leaves. Each pair of guard cells surrounds a stoma, or pore, controlling its ability to open and thus release moisture.

In some situations, external stimuli such as sunlight may cause the guard cells to draw in potassium from other cells. This leads to an increase in osmotic potential: the guard cell becomes like a person who has eaten a dry biscuit, and is now desperate for a drink of water to wash it down. As a result of its increased osmotic potential, the guard cell eventually takes on

water through osmosis. The guard cells then swell with water, opening the stomata and increasing the rate of gas exchange through them. The outcome of this action is an increase in the rate of photosynthesis and plant growth.

When there is a water shortage, however, other cells transmit signals to the guard cells that cause them to release their potassium. This decreases their osmotic potential, and water passes out of the guard cells to the thirsty cells around them. At the same time, the resultant shrinkage in the guard cells closes the stomata, decreasing the rate at which water transpires through them and preventing the plant from wilting.

## Osmosis and Medicine

Osmosis has several implications where medical care is concerned, particularly in the case of the storage of vitally important red blood cells. These are normally kept in a plasma solution which is isotonic to the cells when it contains specific proportions of salts and proteins. However, if red blood cells are placed in a hypotonic solution, or one with a lower solute concentration than in the cells themselves, this can be highly detrimental.

Hence water, a life-giving and life-preserving substance in most cases, is a killer in this context. If red blood cells were stored in pure water, osmosis would draw the water into the cells, causing them to swell and eventually burst. Similarly, if the cells were placed in a solution with a higher solute concentration, or hypertonic solution, osmosis would draw water out of the cells until they shriveled.

In fact, the plasma solution used by most hospitals for storing red blood cells is slightly hypertonic relative to the cells, to prevent them from drawing in water and bursting. Physicians use a similar solution when injecting a drug intravenously into a patient. The active ingredient of the drug has to be suspended in some kind of medium, but water would be detrimental for the reasons discussed above, so instead the doctor uses a saline solution that is slightly hypertonic to the patient's red blood cells.

One vital process closely linked to osmosis is dialysis, which is critical to the survival of many victims of kidney diseases. Dialysis is the process by which an artificial kidney machine removes waste products from a patients' blood—performing the role of a healthy, normally functioning kidney. The openings in the dialyzing membrane are such that not only water, but salts and other waste dissolved in the blood, pass through to a surrounding tank of distilled water. The red blood cells, on the other hand, are too large to enter the dialyzing membrane, so they return to the patient's body.

## Preserving Fruits and Meats

Osmosis is also used for preserving fruits and meats, though the process is quite different for the two. In the case of fruit, osmosis is used to dehydrate it, whereas in the preservation of meat, osmosis draws salt into it, thus preventing the intrusion of bacteria.

Most fruits are about 75% water, and this makes them highly susceptible to spoilage. To preserve fruit, it must be dehydrated, which—as in the case of the salt in the meat— presents bacteria with a less-than-hospitable environment. Over the years, people have tried a variety of methods for drying fruit, but most of these have a tendency to shrink and harden the fruit. The reason for this is that most drying methods, such as heat from the Sun, are relatively quick and drastic; osmosis, on the other hand, is slower, more moderate—and closer to the behavior of nature.

Osmotic dehydration techniques, in fact, result in fruit that can be stored longer than fruit dehydrated by other methods. This in turn makes it possible to provide consumers with a wider variety of fruit throughout the year. Also, the fruit itself tends to maintain more of its flavor and nutritional qualities while keeping out microorganisms.

Because osmosis alone can only remove about 50% of the water in most ripe fruits, however, the dehydration process involves a secondary method as well. First the fruit is blanched, or placed briefly in scalding water to stop enzymatic action. Next it is subjected to osmotic dehydration by dipping it in, or spreading it with, a specially made variety of syrup whose sugar draws out the water in the fruit. After this, air drying or vacuum drying completes the process. The resulting product is ready to eat; can be preserved on a shelf under most climatic conditions; and may even be powdered for making confectionery items.

Whereas osmotic dehydration of fruit is currently used in many parts of the world, the salt-

## KEY TERMS

**HYPERTONIC:** Of higher osmotic pressure.

**HYPOTONIC:** Of lower osmotic pressure.

**ISOTONIC:** Of equal osmotic pressure.

**OSMOSIS:** The movement of a solvent through a semipermeable membrane from a less concentrated solution to a more concentrated one.

**OSMOTIC POTENTIAL:** A difference in osmotic pressure that draws water from an area of less osmotic pressure to an area of greater osmotic pressure.

**OSMOTIC PRESSURE:** The pressure that builds in a substance as it experiences osmosis, and eventually stops that process.

**SOLVENT:** A liquid capable of dissolving or dispersing one or more other substances.

**SOLUTE:** A substance capable of being dissolved in a solvent.

**SOLUTION:** A mixture of solvent and solute.

curing of meat in brine is largely a thing of the past, due to the introduction of refrigeration. Many poorer families, even in the industrialized world, however, remained without electricity long after it spread throughout most of Europe and North America. John Steinbeck's *Grapes of Wrath* (1939) offers a memorable scene in which a contemporary family, the Joads, kill and cure a pig before leaving Oklahoma for California. And a Web site for Walton Feed, an Idaho company specializing in dehydrated foods, offers reminiscences by Canadians whose families were still salt-curing meats in the middle of the twentieth century. Verla Cress of southern Alberta, for instance, offered a recipe from which the following details are drawn.

First a barrel is filled with a solution containing 2 gal (7.57 l) of hot water and 8 oz (.2268 kg) of salt, or 32 parts hot water to one part salt, as well as a small quantity of vinegar. The pig or cow, which would have just been slaughtered, should then be cut up into what Cress called "ham-sized pieces (about 10-15 lb [5-7 kg]) each." The pieces are then soaked in the brine barrel for six days, after which the meat is removed, dried, "and put... in flour or gunny sacks to keep the flies away. Then hang it up in a cool dry place to dry. It will keep like this for perhaps six weeks if stored in a cool place during the Summer. Of course, it will keep much longer in the Winter. If it goes bad, you'll know it!"

Cress offered another method, one still used on ham today. Instead of salt, sugar is used in a mixture of 32 oz (.94 l) to 3 gal (11.36 l) of water. After being removed, the meat is smoked—that is, exposed to smoke from a typically aromatic wood such as hickory, in an enclosed barn—for three days. Smoking the meat tends to make it last much longer: four months in the summer, according to Cress.

The Walton Feeds Web page included another brine-curing recipe, this one used by the women of the Stirling, Alberta, Church of the Latter-Day Saints in 1973. Also included were reminiscences by Glenn Adamson (born 1915): "...When we butchered a pig, Dad filled a wooden 45-gal (170.34 l) barrel with salt brine. We cut up the pig into maybe eight pieces and put it in the brine barrel. The pork soaked in the barrel for several days, then the meat was taken out, and the water was thrown away.... In the hot summer days after they [the pieces of meat] had dried, they were put in the root cellar to keep them cool. The meat was good for eating two or three months this way."

For thousands of years, people used salt to cure and preserve meat: for instance, the sailing ships that first came to the New World carried on board barrels full of cured meat, which fed sailors on the voyage over. Meat was not the only type of food preserved through the use of salt or brine, which is hypertonic—and thus lethal—to bacteria cells. Among other items packed in brine were fish, olives, and vegetables.

Even today, some types of canned fish come to the consumer still packed in brine, as do olives. Another method that survives is the use of

sugar—which can be just as effective as salt for keeping out bacteria—to preserve fruit in jam.

## Reverse Osmosis

Given the many ways osmosis is used for preserving food, not to mention its many interactions with water, it should not be surprising to discover that osmosis can also be used for desalination, or turning salt water into drinking water. Actually, it is not osmosis, strictly speaking, but rather reverse osmosis that turns salt water from the ocean—97% of Earth's water supply—into water that can be used for bathing, agriculture, and in some cases even drinking.

When you mix a teaspoon of sugar into a cup of coffee, as mentioned in an earlier illustration, this is a non-reversible process. Short of some highly complicated undertaking—for instance, using ultrasonic sound waves—it would be impossible to separate solute and solvent.

Osmosis, on the other hand, can be reversed. This is done by using a controlled external pressure of approximately 60 atmospheres, an atmosphere being equal to the air pressure at sea level—14.7 pounds-per-square-inch ($1.013 \times 10^5$ Pa.) In reverse osmosis, this pressure is applied to the area of higher solute concentration—in this case, the seawater. As a result, the pressure in the seawater pushes water molecules into a reservoir of pure water.

If performed by someone with a few rudimentary tools and a knowledge of how to provide just the right amount of pressure, it is possible that reverse osmosis could save the life of a shipwreck victim stranded in a location without a fresh water supply. On the other hand, a person in such a situation may be able to absorb sufficient water from fruits and plant life, as Tom Hanks's character did in the 2001 film *Cast Away*.

Companies such as Reverse Osmosis Systems in Atlanta, Georgia, offer a small unit for home or business use, which actually performs the reverse-osmosis process on a small scale. The unit makes use of a process called crossflow, which continually cleans the semipermeable membrane of impurities that have been removed from the water. A small pump provides the pressure necessary to push the water through the membrane. In addition to an under-the-sink model, a reverse osmosis water cooler is also available.

Not only is reverse osmosis used for making water safe, it is also applied to metals in a variety of capacities, not least of which is its use in treating wastewater from electroplating. But there are other metallurgical methods of reverse osmosis that have little to do with water treatment: metal finishing, as well as recycling of metals and chemicals. These processes are highly complicated, but they involve the same principle of removing impurities that governs reverse osmosis.

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# DISTILLATION AND FILTRATION

## CONCEPT

When most people think of chemistry, they think about joining substances together. Certainly, the bonding of elements to form compounds through chemical reactions is an integral component of the chemist's study; but chemists are also concerned with the separation of substances. Some forms of separation, in which compounds are returned to their elemental form, or in which atoms split off from molecules to yield a compound and a separated element, are complex phenomena that require chemical reactions. But chemists also use simpler physical methods, distillation and filtration, to separate mixtures. Distillation can be used to purify water, make alcohols, or separate petroleum into various components that range from natural gas to gasoline to tar. Filtration also makes possible the separation of gases or liquids from solids, and sewage treatment—a form of filtration—separates liquids, solids, and gases through a series of chemical and physical processes.

## HOW IT WORKS

### Mixtures: Homogeneous and Heterogeneous

In contrast to a pure substance, a class that includes only elements and compounds, mixtures constitute a much broader category. Usually, a mixture consists of many compounds mixed together, but it is possible to have a mixture (air is an example) in which elemental substances are combined with compounds. Elements alone can be combined in a mixture, as when copper and zinc are alloyed to make brass. It is also possible to have a mixture of mixtures, as for example when milk (a particular type of mixture called an emulsion) is added to coffee.

It is sometimes difficult, without studying the chemical aspects involved, to recognize the difference between a mixture and a pure substance. A mixture, however, can be defined as a substance with a variable composition, meaning that if more of one component is added, it does not change the essential character of the mixture. People unconsciously recognize this when they joke, "Would you like a little coffee with your milk?"

This comment, made when someone puts a great quantity of milk into a cup of coffee, implies that we generally regard coffee and milk as a solution in which the coffee dissolves the milk. But even if someone made a cup of coffee that was half milk, so that the resulting substance had a vanilla-like color, we would still call it coffee. If the components of a pure substance are altered, however, it becomes something entirely different.

Two hydrogen atoms bonded to an oxygen atom create water, but when two hydrogen atoms bond to two oxygen atoms, this is hydrogen peroxide, an altogether different substance. Water at ordinary temperatures does not bubble, whereas hydrogen peroxide does. Hydrogen peroxide boils at a temperature more than 1.5 times the boiling point of water, and potatoes boiled in hydrogen peroxide would be nothing like potatoes boiled in water. Eating them, in fact, could very well be fatal.

**HOMOGENEOUS VS. HETEROGENEOUS.** Unlike a compound or element, a mixture can never be broken down to a single type of molecule or atom, yet there are mixtures

that appear to be the same throughout. These are called homogeneous mixtures, in which the properties and characteristics are the same throughout the mixture. In a heterogeneous mixture, on the other hand, the composition is not the same throughout, and in fact the mixture is separated into regions with varying properties.

Chemists of the past sometimes had difficulty distinguishing between homogeneous mixtures—virtually all of which can be described as solutions—and pure substances. Air, for example, appears to be a pure substance; yet there is no such thing as an "air molecule." Instead, air is composed primarily of nitrogen and oxygen, which appear in molecular rather than atomic form, along with separated atoms of noble gases and two important compounds: carbon dioxide and water. (Water exists in air as a vapor.)

There is less probability of confusing a heterogeneous mixture with a pure substance, because one of the defining aspects of a heterogeneous substance is the fact that it is clearly a mixture. When sand is added to a container of water, and the sand sinks to the bottom, it is obvious that there is no "sand-and-water" molecule pervading the entire mixture. Clearly, the upper portion of the container is mostly water, and the lower portion mostly sand.

### Separating Mixtures

There are two basic processes for separating mixtures, distillation and filtration. In general, these are applied for the separation of homogeneous and heterogeneous mixtures, respectively. Distillation is the use of heat to separate the components of a liquid and/or gas, while filtration is the separation of solids from a fluid (either a gas or a liquid) by allowing the fluid to pass through a filter.

In a solution such as salt water, there are two components: the solvent (the water) and the solute (the salt). These can be separated by distillation in a laboratory using a burner placed under a beaker containing the salt water. As the water is heated, it passes out of the beaker in the form of steam, and travels through a tube cooled by a continual flow of cold water. Inside the tube, the steam condenses to form liquid water, which passes into a second beaker. Eventually, all of the solvent will be distilled from the first beaker, leaving behind the salt that constituted the solute of the original solution.

Distillation may seem like a chemical process, but in fact it is purely physical, because the composition of neither compound—salt or water—has been changed. As for filtration, it is clearly a physical process, just as heterogeneous mixtures are more obviously mixtures and not compounds. Suppose we wanted to separate the heterogeneous mixture we described earlier, of sand in water: all we would need would be a mesh screen through which the liquid could be strained, leaving behind the sand.

Despite the apparent simplicity of filtration, it can become rather complicated, as we shall see, in the treatment of sewage to turn it into water that poses no threat to the environment. Furthermore, it should be noted that sometimes these processes—distillation and filtration—are used in tandem. Suppose we had a mixture of sand and salt water taken from the beach, and we wanted to separate the mixture. The first step would involve the simpler process of filtration, separating the sand from the salt water. This would be followed by the separation of pure water and salt through the distillation process.

## REAL-LIFE APPLICATIONS

### Distillation

In distillation, the more volatile component of the mixture—that is, the part that is more easily vaporized—is separated from the less volatile portion. With regard to the illustration used above, of separating water from salt, clearly the water is the more volatile portion: its boiling point is much, much lower than that of salt, and the heat required to vaporize the salt is so great that the water would be long since vaporized by the time the salt was affected.

Once the volatile portion has been vaporized, or turned into distillate, it experiences condensation—the cooling of a gas to form a liquid, after which the liquid or condensate is collected. Note that in all these stages of distillation, heat is the agent of separation. This is especially important in the process of fractional distillation, discussed below.

The process of removing water vapor from salt water, described earlier, is an example of what is called "single-stage differential distillation." Sometimes, however—especially when a



A water filtration plant in Contra Costa County, California. *(James A. Sugar/Corbis. Reproduced by permission.)*

high level of purity in the resulting condensate is desired—it may be necessary to subject the condensate to multiple processes of distillation to remove additional impurities. This process is called rectification.

**PURIFIED WATER AND ETHANOL.** If distillation can be used to separate water from salt, obviously it can also be used to separate water from microbes and other impurities through a more detailed process of rectification. Distilled water, purchased for drinking and other purposes, is just one of the more common applications of the distillation process. Another well-known use of this process is the production of ethyl alcohol, made famous (or perhaps infamous) by stories of bootleggers producing homemade whiskey from "stills" or distilleries in the woods.

Ethanol, the alcohol in alcoholic beverages, is produced by the fermentation of glucose, a sugar found in various natural substances. The choice of substances is a function of the desired product: grapes for wine; barley and hops for beer; juniper berries for gin; potatoes for vodka, and so on. Glucose reacts with yeast, fermenting to yield ethanol, and this reaction is catalyzed by enzymes in the yeast. The reaction continues until the alcohol content reaches a point equal to about 13%.

After that point, the yeast enzymes can no longer survive, and this is where the production of beer or wine usually ends. Fortified wine or



Few industries employ distillation to a greater degree than does the petroleum industry. Shown here is an oil refinery. *(Mark L. Stephenson/Corbis. Reproduced by permission.)*

malt liquor—variations of wine and beer, respectively, that are more than 13% alcohol, or 26 proof—are exceptions. These two products are the result of mixtures between undistilled beer and wine and products of distillation having a higher alcohol content.

Distillation constitutes the second stage in the production of alcohol. Often, the fermentation products are subjected to a multistage rectification process, which yields a mixture of up to 95% ethanol and 5% water. This mixture is called an azeotrope, meaning that it will not change composition when distilled further. Usually the production of whiskey or other liquor stops well below the point of yielding an azeotrope, but in some states, brands of grain alcohol at 190 proof (95%) are sold.

**INDUSTRIAL DISTILLATION.** In contrast to ethanol, methanol or "wood alcohol" is a highly toxic substance whose ingestion can lead to blindness or death. It is widely used in industry for applications in adhesives, plastics, and other products, and was once produced by the distillation of wood. In this old production method, wood was heated in the absence of air, such that it did not burn, but rather decomposed into a number of chemicals, a fraction of which were methanol and other alcohols.

The distillation of wood alcohol was abandoned for a number of reasons, not least of which was the environmental concern: thou-

sands of trees had to be cut down for use in an inefficient process yielding only small portions of the desired product. Today, methanol is produced from synthesis gas, itself a product of coal gasification; nonetheless, numerous industrial processes use distillation.

Distillation is employed, for instance, to separate the hydrocarbons benzene and toluene, as well as acetone from acetic acid. In nuclear power plants that require quantities of the hydrogen isotope deuterium, the lighter protium isotope, or plain hydrogen, is separated from the heavier deuterium by means of distillation. Few industries, however, employ distillation to a greater degree than the petroleum industry.

Through a process known as fractional distillation, oil companies separate hydrocarbons from petroleum, allowing those of lower molecular mass to boil off and be collected first. For instance, at temperatures below 96.8°F (36°C), natural gas separates from petroleum. Other substances, including petroleum ether and naphtha, separate before the petroleum reaches the 156.2°F-165.2°F (69°C-74°C) range, at which point gasoline separates.

Fractional distillation continues, with the separation of other substances, all the way up to 959°F (515°C), above which tar becomes the last item to be separated. Petroleum and petroleum-product companies account for a large portion of the more than 40,000 distillation units in operation across the country. About 95% of all industrial separation processes involve distillation, which consumes large amounts of energy; for that reason, ever more efficient forms of distillation are continually being researched.

## Filtration

In the simplest form of filtration, described earlier, a suspension (solid particles floating in a liquid) is allowed to pass through filter paper supported in a glass funnel. The filter paper traps the solid particles, allowing a clear solution (the filtrate) to pass through the funnel and into a receiving container.

There are two basic purposes for filtration: either to capture the solid material suspended in the fluid, or to clarify the fluid in which the solid is suspended. An example of the former occurs, for instance, when panning for gold: the water is allowed to pass through a sieve, leaving behind rocks that—the prospector hopes—contain gold. An example of the latter occurs in sewage treatment. Here the solid left behind is feces—as undesirable as gold is desirable.

Filtration can further be classified as either gaseous or liquid, depending on which of the fluids constitutes the filtrate. Furthermore, the force that moves the fluid through the filter—whether gravity, a vacuum, or pressure—is another defining factor. The type of filter used can also serve to distinguish varieties of filtration.

**Liquid filtration.** In liquid filtration, such as that applied in sewage treatment, a liquid can be pulled through the filter by gravitational force, as in the examples given. On the other hand, some sort of applied pressure, or a pressure differential created by the existence of a vacuum, can force the liquid through the filter.

Water filtration for purification purposes is often performed by means of gravitation. Usually, water is allowed to run down through a thick layer of granular material such as sand, gravel, or charcoal, which removes impurities. These layers may be several feet thick, in which case the filter is known as a deep-bed filter. Water purification plants may include fine particles of charcoal, known as activated carbon, in the deep-bed filter to absorb unpleasant-smelling gases.

For separating smaller volumes of solution, a positive-pressure system—one that uses external pressure to push the liquid through the filter—may be used. Fluid may be introduced under pressure at one end of a horizontal tank, then forced through a series of vertical plates covered with thick filtering cloths that collect solids. In a vacuum filter, a vacuum (an area virtually devoid of matter, including air) is created beneath the solution to be filtered, and as a result, atmospheric pressure pushes the liquid through the filter.

When the liquid is virtually freed of impurities, it may be passed through a second variety of filter, known as a clarifying filter. This type of filter is constructed of extremely fine-mesh wires or fibers designed to remove the smallest particles suspended in the liquid. Clarifying filters may also use diatomaceous earth, a finely powdered material produced from the decay of marine organisms.

**Gas filtration.** Gas filtration is used in a common appliance, the vacuum cleaner, which passes a stream of dust-filled air

## KEY TERMS

**AZEOTROPE:** A solution that has been subjected through distillation and is still not fully separated, but cannot be separated any further by means of distillation. An example is ethanol, which cannot be distilled beyond the point at which it reaches a 95% concentration with water.

**CONDENSATE:** The liquid product that results from distillation.

**CONDENSATION:** The cooling of a gas to form a liquid or condensate.

**DISTILLATE:** The vapor collected from the volatile material or materials in distillation. This vapor is then subjected to condensation.

**DISTILLATION:** The use of heat to separate the components of a liquid and/or gas. Generally, distillation is used to separate mixtures that are homogeneous.

**FILTRATE:** The liquid or gas separated from a solid by means of filtration.

**FILTRATION:** The separation of solids from a fluid (either gas or liquid) by allowing the fluid to pass through a filter. Generally, filtration is used to separate mixtures that are heterogeneous.

**HETEROGENEOUS:** A term describing a mixture that is not the same throughout; rather, it has various regions possessing different properties. An example is sand in a container of water.

**HOMOGENEOUS:** A term describing a mixture that is the same throughout, as for example when sugar is fully dissolved in water. A solution is a homogenous mixture.

**MIXTURE:** A substance with a variable composition, composed of molecules or atoms of differing types. Compare with pure substance.

**PURE SUBSTANCE:** A substance—either an element or compound—that has an unvarying composition. This means that by changing the proportions of atoms, the result would be an entirely different substance. Compare with mixture.

**SOLUTE:** The substance or substances that are dissolved in a solvent to form a solution.

**SOLUTION:** A homogeneous mixture in which one or more substances is dissolved in an another substance—for example, sugar dissolved in water.

**SOLVENT:** The substance that dissolves a solute to form a solution.

**SUSPENSION:** A term that refers to a mixture in which solid particles are suspended in a fluid.

**VOLATILE:** Easily vaporized.

through a filtering bag inside the machine. The bag traps solid particles, while allowing clean air to pass back out into the room. This is essentially the same principle applied in air filters and even air conditioning and heating systems, which, in addition to regulating temperature, also remove dust, pollen, and other impurities from the air.

Various industries use gas filtration, not only to purify the products released into the atmosphere, but also to filter the air in the workplace, as for instance in a factory room where fine airborne particles are a hazard of production. The gases from power plants that burn coal and oil are often purified by passing them through filtering systems that collect particles.

## Sewage Treatment

Sewage treatment is a complex, multistage process whereby waste water is freed of harmful contents and rendered safe, so that it can be returned to the environment. This is a critical part of modern life, because when people congregate in cities, they generate huge amounts of wastes that contain disease-causing bacteria, viruses, and other microorganisms. Lack of proper waste management in ancient and medieval times led to devastating plagues in cities such as Athens, Rome, and Constantinople.

Indeed, one of the factors contributing to the end of the Athenian golden age of the fifth century B.C. was a plague, caused by lack of proper sewage-disposal methods, that felled many of the city's greatest figures. The horrors created by improper waste management reached their apogee in 1347-51, when microorganisms carried by rats brought about the Black Death, in which Europe's population was reduced by one-third.

**AEROBIC AND ANAEROBIC DECAY.** Small amounts of sewage can be dealt with through aerobic (oxygen-consuming) decay, in which microorganisms such as bacteria and fungi process the toxins in human waste. With larger amounts of waste, however, oxygen is depleted and the decay mechanism must be anaerobic, or carried out in the absence of oxygen.

For people who are not connected to a municipal sewage system, and therefore must rely on a septic tank for waste disposal, waste products pass through a tank in which they are subjected to anaerobic decay by varieties of microorganisms that do not require oxygen to survive. From there, the waste goes through the drain field, a network of pipes that allow the water to seep into a deep-bed filter. In the drain field, the waste is subjected to aerobic decay by oxygen-dependant microorganisms before it either filters through the drain pipes into the ground, or is evaporated.

**MUNICIPAL WASTE TREATMENT.** Municipal waste treatment is a much more involved process, and will only be described in the most general terms here. Essentially, large-scale sewage treatment requires the separation of larger particles first, followed by the separation of smaller particles, as the process continues. Along the way, the sewage is chemically treated as well. The separation of smaller solid particles is aided by aluminum sulfate, which causes these particles to settle to the bottom more rapidly.

Through continual processing by filtration, water is eventually clarified of biosolids (that is, feces), but it is still far from being safe. At that point, all the removed biosolids are dried and incinerated; or they may be subjected to additional processes to create fertilizer. The water, or effluent, is further clarified by filtration in a deep-bed filter, and additional air may be introduced to the water to facilitate aerobic decay—for instance, by using algae.

Through a long series of such processes, the water is rendered safe to be released back into the environment. However, wastes containing extremely high levels of toxins may require additional or different forms of treatment.

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# ORGANIC CHEMISTRY

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# ORGANIC CHEMISTRY

## CONCEPT

There was once a time when chemists thought "organic" referred only to things that were living, and that life was the result of a spiritual "life force." While there is nothing wrong with viewing life as having a spiritual component, spiritual matters are simply outside the realm of science, and to mix up the two is as silly as using mathematics to explain love (or vice versa). In fact, the "life force" has a name: carbon, the common denominator in all living things. Not everything that has carbon is living, nor are all the areas studied in organic chemistry—the branch of chemistry devoted to the study of carbon and its compounds—always concerned with living things. Organic chemistry addresses an array of subjects as vast as the number of possible compounds that can be made by strings of carbon atoms. We can thank organic chemistry for much of what makes life easier in the modern age: fuel for cars, for instance, or the plastics found in many of the products used in an average day.

## HOW IT WORKS

### Introduction to Carbon

As the element essential to all of life, and hence the basis for a vast field of study, carbon is addressed in its own essay. The Carbon essay, in addition to examining the chemical properties of carbon (discussed below), approaches a number of subjects, such as the allotropes of carbon. These include three crystalline forms (graphite, diamond, and buckminsterfullerene), as well as amorphous carbon. In addition, two oxides of carbon—carbon dioxide and carbon monoxide—are important, in the case of the former, to the natural carbon cycle, and in the case of the latter, to industry. Both also pose environmental dangers.

The purpose of this summary of the carbon essay is to provide a hint of the complexities involved with this sixth element on the periodic table, the 14th most abundant element on Earth. In the human body, carbon is second only to oxygen in abundance, and accounts for 18% of the body's mass. Capable of combining in seemingly endless ways, carbon, along with hydrogen, is at the center of huge families of compounds. These are the hydrocarbons, present in deposits of fossil fuels: natural gas, petroleum, and coal.

**A PROPENSITY FOR LIMITLESS BONDING.** Carbon has a valence electron configuration of $2s^2 2p^2$. Likewise all the members of Group 4 on the periodic table (Group 14 in the IUPAC version of the table)—sometimes known as the "carbon family"—have configurations of $ns^2np^2$, where n is the number of the period or row the element occupies on the table. 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 is at the center of a vast network of organic compounds, silicon holds the same function in the inorganic realm. It is found in virtually all types of rocks, except the calcium carbonates—which, as their name implies, contain carbon. In terms of known elemental mass, silicon is second only to oxygen in abundance on Earth. Silicon atoms are about one and a half times as large as those of carbon; thus not even silicon can compete with carbon's ability to form



"I just want to say one word to you...plastics." Signifying that plastics were the wave of the future, these words were uttered to Dustin Hoffman's character in the 1967 film The Graduate. *(The Kobal Collection. Reproduced by permission.)*

an almost limitless array of molecules in various shapes and sizes, and with various chemical properties.

## Electronegativity

Carbon is further distinguished by its high value of electronegativity, the relative ability of an atom to attract valence electrons. To mention a few basic aspects of chemical bonding, developed at considerably greater length in the Chemical Bonding essay, if two atoms have an electric charge and thus are ions, they form strong ionic bonds. Ionic bonding occurs when a metal bonds with a nonmetal. The other principal type of bond is a covalent bond, in which two uncharged atoms share eight valence electrons. If the electronegativity values of the two elements involved are equal, then they share the electrons equally; but if one element has a higher electronegativity value, the electrons will be more drawn to that element.

The electronegativity of carbon is certainly not the highest on the periodic table. That distinction belongs to fluorine, with an electronegativity value of 4.0, which makes it the most reactive of all elements. Fluorine is at the head of Group 7, the halogens, all of which are highly reactive and most of which have high electronegativity values. If one ignores the noble gases, which are virtually unreactive and occupy the extreme right-hand side of the periodic table, electronegativity values are highest in the upper right-hand side of the table—the location of fluorine—and lowest in the lower left. In other words, the value increases with group or column number (again, leaving out the noble gases in Group 8), and decreases with period or row number.

With an electronegativity of 2.5, carbon ties with sulfur and iodine (a halogen) for sixth place, behind only fluorine; oxygen (3.5); nitrogen and chlorine (3.0); and bromine (2.8). Thus its electronegativity is high, without being too high. Fluorine is not likely to form the long chains for which is carbon is known, simply because its electronegativity is so high, it overpowers other elements with which it comes into contact. In addition, with four valence electrons, carbon is ideally suited to find other elements (or other carbon atoms) for forming covalent bonds according to the octet rule, whereby most elements bond so that they have eight valence electrons.

### Carbon's Multiple Bonds

Carbon—with its four valence electrons—happens to be tetravalent, or capable of bonding to four other atoms at once. It is not necessarily the case that an element has the ability to bond with as many other elements as it has valence electrons; in fact, this is rarely the case. Additionally, carbon is capable of forming not only a single bond, with one pair of shared valence electrons, but a double bond (two pairs) or even a triple bond (three pairs.)

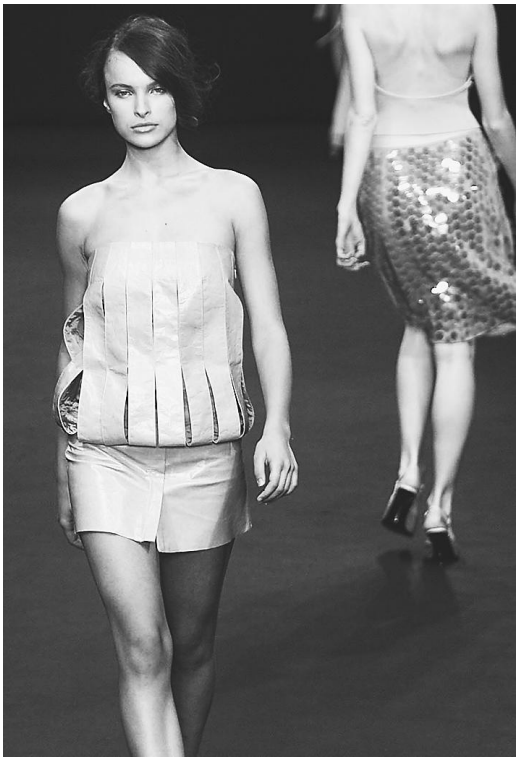
Another special property of carbon is its ability to bond in long chains that constitute strings of carbons and other atoms. Furthermore, though sometimes carbon forms a typical molecule (for example, carbon dioxide, or $CO_2$, is just one carbon atom with two oxygens), it is also capable of forming "molecules" that are really not molecules in the way that the word is typically used in chemistry. Graphite, for instance, is just a series of "sheets" of carbon atoms bonded tightly in a hexagonal, or six-sided, pattern, while a diamond is simply a huge "molecule" composed of carbon atoms strung together by covalent bonds.

### Organic Chemistry

Organic chemistry is the study of carbon, its compounds, and their properties. The only major carbon compounds considered inorganic are carbonates (for instance, calcium carbonate, alluded to above, which is one of the major forms of mineral on Earth) and oxides, such as carbon dioxide and carbon monoxide. This leaves a huge array of compounds to be studied, as we shall see.

The term "organic" in everyday language connotes "living," but organic chemistry is involved with plenty of compounds not part of living organisms: petroleum, for instance, is an organic compound that ultimately comes from the decayed bodies of organisms that once were alive. It should be stressed that organic compounds do not have to be produced by living things, or even by things that once were alive; they can be produced artificially in a laboratory.

The breakthrough event in organic chemistry came in 1828, when German chemist Friedrich Wöhler (1800-1882) heated a sample of ammonium cyanate ($NH_4OCN$) and converted it to urea ($H_2N\text{-}CO\text{-}NH_2$). Ammonium cyanite is an inorganic material, whereas urea, a waste product in the urine of mammals, is an organic one. "Without benefit of a kidney, a bladder, or a dog," as Wöhler later said, he had managed to transform an inorganic substance into an organic one.



It is virtually impossible for a person in modern America to spend an entire day without coming into contact with at least one, and more likely dozens, of plastic products, all made possible by organic chemistry. Here, a fashion model parades a dress made of PVC. *(Reuters NewMedia Inc./Corbis. Reproduced by permission.)*

Ammonium cyanate and urea are isomers: substances having the same formula, but possessing different chemical properties. Thus they have exactly the same numbers and proportions of atoms, yet these atoms are arranged in different ways. In urea, the carbon forms an organic chain, and in ammonium cyanate, it does not. Thus, to reduce the specifics of organic chemistry even further, this discipline can be said to constitute the study of carbon chains, and ways to rearrange them to create new substances.

## REAL-LIFE APPLICATIONS

### Organic Chemistry and Modern Life

At first glance, the term "organic chemistry" might sound like something removed from



Another byproduct of organic chemistry: petroleum jelly. *(Laura Dwight/Corbis. Reproduced by permission.)*

everyday life, but this could not be further from the truth. The reality of the role played by organic chemistry in modern existence is summed up in a famous advertising slogan used by E. I. du Pont de Nemours and Company (usually referred to as "du Pont"): "Better Things for Better Living Through Chemistry."

Often rendered simply as "Better Living Through Chemistry," the advertising campaign made its debut in 1938, just as du Pont introduced a revolutionary product of organic chemistry: nylon, the creation of a brilliant young chemist named Wallace Carothers (1896-1937). Nylon, an example of a polymer (discussed below), started a revolution in plastics that was still unfolding three decades later, in 1967. That was the year of the film *The Graduate*, which included a famous interchange between the character of Benjamin Braddock (Dustin Hoffman) and an adult named Mr. McGuire (Walter Brooke):

- Mr. McGuire: I just want to say one word to you... just one word.
- Benjamin Braddock: Yes, sir.
- Mr. McGuire: Are you listening?
- Benjamin Braddock: Yes, sir, I am.
- Mr. McGuire: Plastics.

The meaning of this interchange was that plastics were the wave of the future, and that an intelligent young man such as Ben should invest his energies in this promising new field. Instead, Ben puts his attention into other things, quite removed from "plastics," and much of the plot revolves around his revolt against what he perceives as the "plastic" (that is, artificial) character of modern life.

In this way, *The Graduate* spoke for a whole generation that had become ambivalent concerning "better living through chemistry," a phrase that eventually was perceived as ironic in view of concerns about the environment and the many artificial products that make up modern life. Responding to this ambivalence, du Pont dropped the slogan in the late 1970s; yet the reality is that people truly do enjoy "better living through chemistry"—particularly organic chemistry.

**APPLICATIONS OF ORGANIC CHEMISTRY.** What would the world be like without the fruits of organic chemistry? First, it would be necessary to take away all the various forms of rubber, vitamins, cloth, and paper made from organically based compounds. Aspirins and all types of other drugs; preservatives that keep food from spoiling; perfumes and toiletries; dyes

and flavorings—all these things would have to go as well.

Synthetic fibers such as nylon—used in everything from toothbrushes to parachutes—would be out of the picture if it were not for the enormous progress made by organic chemistry. The same is true of plastics or polymers in general, which have literally hundreds upon hundreds of applications. Indeed, it is virtually impossible for a person in twenty-first century America to spend an entire day without coming into contact with at least one, and more likely dozens, of plastic products. Car parts, toys, computer housings, Velcro fasteners, PVC (polyvinyl chloride) plumbing pipes, and many more fixtures of modern life are all made possible by plastics and polymers.

Then there is the vast array of petrochemicals that power modern civilization. Best-known among these is gasoline, but there is also coal, still one of the most significant fuels used in electrical power plants, as well as natural gas and various other forms of oil used either directly or indirectly in providing heat, light, and electric power to homes. But the influence of petrochemicals extends far beyond their applications for fuel. For instance, the roofing materials and tar that (quite literally) keep a roof over people's heads, protecting them from sun and rain, are the product of petrochemicals—and ultimately, of organic chemistry.

## HYDROCARBONS

Carbon, together with other elements, forms so many millions of organic compounds that even introductory textbooks on organic chemistry consist of many hundreds of pages. Fortunately, it is possible to classify broad groupings of organic compounds. The largest and most significant is that class of organic compounds known as hydrocarbons—chemical compounds whose molecules are made up of nothing but carbon and hydrogen atoms.

Every molecule in a hydrocarbon is built upon a "skeleton" composed of carbon atoms, either in closed rings or in long chains. The chains may be straight or branched, but in each case—rings or chains, straight chains or branched ones—the carbon bonds not used in tying the carbon atoms together are taken up by hydrogen atoms.

Theoretically, there is no limit to the number of possible hydrocarbons. Not only does carbon form itself into apparently limitless molecular shapes, but hydrogen is a particularly good partner. It has the smallest atom of any element on the periodic table, and therefore it can bond to one of carbon's valence electrons without getting in the way of the other three.

There are two basic varieties of hydrocarbon, distinguished by shape: aliphatic and aromatic. The first of these forms straight or branched chains, as well as rings, while the second forms only benzene rings, discussed below. Within the aliphatic hydrocarbons are three varieties: those that form single bonds (alkanes), double bonds (alkenes), and triple bonds (alkynes.)

**ALKANES.** The alkanes are also known as saturated hydrocarbons, because all the bonds not used to make the skeleton itself are filled to their capacity (that is, saturated) with hydrogen atoms. The formula for any alkane is $C_nH_{2n+2}$, where n is the number of carbon atoms. In the case of a linear, unbranched alkane, every carbon atom has two hydrogen atoms attached, but the two end carbon atoms each have an extra hydrogen.

What follows are the names and formulas for the first eight normal, or unbranched, alkanes. Note that the first four of these received common names before their structures were known; from $C_5$ onward, however, they were given names with Greek roots indicating the number of carbon atoms (e.g., octane, a reference to "eight.")

- Methane ($CH_4$)
- Ethane ($C_2H_6$)
- Propane ($C_3H_8$)
- Butane ($C_4H_{10}$)
- Pentane ($C_5H_{12}$)
- Hexane ($C_6H_{14}$)
- Heptane ($C_7H_{16}$)
- Octane ($C_8H_{18}$)

The reader will undoubtedly notice a number of familiar names on this list. The first four, being the lowest in molecular mass, are gases at room temperature, while the heavier ones are oily liquids. Alkanes even heavier than those on this list tend to be waxy solids, an example being paraffin wax, for making candles. It should be noted that from butane on up, the alkanes have numerous structural isomers, depending on

whether they are straight or branched, and these isomers have differing chemical properties.

Branched alkanes are named by indicating the branch attached to the principal chain. Branches, known as substituents, are named by taking the name of an alkane and replacing the suffix with yl—for example, methyl, ethyl, and so on. The general term for an alkane which functions as a substituent is alkyl.

Cycloalkanes are alkanes joined in a closed loop to form a ring-shaped molecule. They are named by using the names above, with cyclo- as a prefix. These start with propane, or rather cyclopropane, which has the minimum number of carbon atoms to form a closed shape: three atoms, forming a triangle.

**ALKENES AND ALKYNES.** The names of the alkenes, hydrocarbons that contain one or more double bonds per molecule, are parallel to those of the alkanes, but the family ending is -ene. Likewise they have a common formula: $C_nH_{2n}$. Both alkenes and alkynes, discussed below, are unsaturated—in other words, some of the carbon atoms in them are free to form other bonds. Alkenes with more than one double bond are referred to as being polyunsaturated.

As with the alkenes, the names of alkynes (hydrocarbons containing one or more triple bonds per molecule) are parallel to those of the alkanes, only with the replacement of the suffix -yne in place of -ane. The formula for alkenes is $C_nH_{2n-2}$. Among the members of this group are acetylene, or $C_2H_2$, used for welding steel. Plastic polystyrene is another important product from this division of the hydrocarbon family.

**AROMATIC HYDROCARBONS.** Aromatic hydrocarbons, despite their name, do not necessarily have distinctive smells. In fact the name is a traditional one, and today these compounds are defined by the fact that they have benzene rings in the middle. Benzene has a formula $C_6H_6$, and a benzene ring is usually represented as a hexagon (the six carbon atoms and their attached hydrogen atoms) surrounding a circle, which represents all the bonding electrons as though they were everywhere in the molecule at once.

In this group are products such 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.

**PETROCHEMICALS.** As for petrochemicals, these are simply derivatives of petroleum, itself a mixture of alkanes with some alkenes, as well as aromatic hydrocarbons. Through a process known as fractional distillation, the petrochemicals of the lowest molecular mass boil off first, and those having higher mass separate at higher temperatures.

Among the products derived from the fractional distillation of petroleum are the following, listed from the lowest temperature range (that is, the first material to be separated) to the highest: natural gas; petroleum ether, a solvent; naphtha, a solvent (used for example in paint thinner); gasoline; kerosene; fuel for heating and diesel fuel; 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.

Obviously, petroleum is not just for making gasoline, though of course this is the first product people think of when they hear the word "petroleum." Not all hydrocarbons in gasoline are desirable. Straight-chain or normal heptane, for instance, does not fire smoothly in an internal-combustion engine, and therefore disrupts the engine's rhythm. For this reason, it is given 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 presence of octane, the better the gas is for one's automobile.

## Hydrocarbon Derivatives

With carbon and hydrogen as the backbone, the hydrocarbons are capable of forming a vast array of hydrocarbon derivatives by combining with other elements. These other elements are arranged in functional groups—an atom or group of atoms whose presence identifies a specific family of compounds. Below we will briefly discuss some of the principal hydrocarbon deriv-

atives, which are basically hydrocarbons with the addition of other molecules or single atoms.

Alcohols are oxygen-hydrogen molecules wedded to hydrocarbons. The two most important commercial types of alcohol are methanol, or wood alcohol; and ethanol, which is found in alcoholic beverages, such as beer, wine, and liquor. Though methanol is still known as "wood alcohol," it is no longer obtained by heating wood, but rather by the industrial hydrogenation of carbon monoxide. Used in adhesives, fibers, and plastics, it can also be applied as a fuel. Ethanol, too, can be burned in an internal-combustion engine, when combined with gasoline to make gasohol. Another significant alcohol is cholesterol, found in most living organisms. Though biochemically important, cholesterol can pose a risk to human health.

Aldehydes and ketones both involve a double-bonded carbon-oxygen molecule, known as a carbonyl group. In a ketone, the carbonyl group bonds to two hydrocarbons, while in an aldehyde, the carbonyl group is always at the end of a hydrocarbon chain. Therefore, instead of two hydrocarbons, there is always a hydrocarbon and at least one other hydrogen bonded to the carbon atom in the carbonyl. One prominent example of a ketone is acetone, used in nail polish remover. Aldehydes often appear in nature—for instance, as vanillin, which gives vanilla beans their pleasing aroma. The ketones carvone and camphor impart the characteristic flavors of spearmint leaves and caraway seeds.

**CARBOXYLIC ACIDS AND ESTERS.** Carboxylic acids all have in common what is known as a carboxyl group, designated by the symbol -COOH. This consists of a carbon atom with a double bond to an oxygen atom, and a single bond to another oxygen atom that is, in turn, wedded to a hydrogen. All carboxylic acids can be generally symbolized by RCOOH, with R as the standard designation of any hydrocarbon. Lactic acid, generated by the human body, is a carboxylic acid: when a person overexerts, the muscles generate lactic acid, resulting in a feeling of fatigue until the body converts the acid to water and carbon dioxide. Another example of a carboxylic acid is butyric acid, responsible in part for the smells of rancid butter and human sweat.

When a carboxylic acid reacts with an alcohol, it forms an ester. An ester has a structure similar to that described for a carboxylic acid, with a few key differences. In addition to its bonds (one double, one single) with the oxygen atoms, the carbon atom is also attached to a hydrocarbon, which comes from the carboxylic acid. Furthermore, the single-bonded oxygen atom is attached not to a hydrogen, but to a second hydrocarbon, this one from the alcohol. One well-known ester is acetylsalicylic acid—better known as aspirin. Esters, which are a key factor in the aroma of various types of fruit, are often noted for their pleasant smell.

## POLYMERS

Polymers are long, stringy molecules made of smaller molecules called monomers. They appear in nature, but thanks to Carothers—a tragic figure, who committed suicide a year before Nylon made its public debut—as well as other scientists and inventors, synthetic polymers are a fundamental part of daily life.

The structure of even the simplest polymer, polyethylene, is far too complicated to discuss in ordinary language, but must be represented by chemical symbolism. Indeed, polymers are a subject unto themselves, but it is worth noting here just how many products used today involve polymers in some form or another.

Polyethylene, for instance, is the plastic used in garbage bags, electrical insulation, bottles, and a host of other applications. A variation on polyethylene is Teflon, used not only in nonstick cookware, but also in a number of other devices, such as bearings for low-temperature use. Polymers of various kinds are found in siding for houses, tire tread, toys, carpets and fabrics, and a variety of other products far too lengthy to enumerate.

## WHERE TO LEARN MORE

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## KEY TERMS

**ALKANES:** Hydrocarbons that form single bonds. Alkanes are also called saturated hydrocarbons.

**ALKENES:** Hydrocarbons that form double bonds.

**ALKYL:** A general term for an alkane that functions as a substituent.

**ALKYNES:** Hydrocarbons that form triple bonds.

**ALLOTROPES:** Different versions of the same element, distinguished by molecular structure.

**AMORPHOUS:** Having no definite structure.

**COVALENT BONDING:** A type of chemical bonding in which two atoms share valence electrons.

**CRYSTALLINE:** A term describing a type of solid in which the constituent parts have a simple and definite geometric arrangement repeated in all directions.

**DOUBLE BOND:** A form of bonding in which two atoms share two pairs of valence electrons. Carbon is also capable of single bonds and triple bonds.

**ELECTRONEGATIVITY:** The relative ability of an atom to attract valence electrons.

**FUNCTIONAL GROUPS:** An atom or group of atoms whose presence identifies a specific family of compounds.

**HYDROCARBON:** Any chemical compound whose molecules are made up of nothing but carbon and hydrogen atoms.

**HYDROCARBON DERIVATIVES:** Families of compounds formed by the joining of hydrocarbons with various functional groups.

**ISOMERS:** Substances having the same chemical formula, but that are different chemically due to disparities in the arrangement of atoms.

**OCTET RULE:** A term describing the distribution of valence electrons that takes place in chemical bonding for most elements, which end up with eight valence electrons.

**ORGANIC CHEMISTRY:** The study of carbon, its compounds, and their properties. (Some carbon-containing compounds, most notably oxides and carbonates, are not considered organic.)

**SATURATED:** A term describing a hydrocarbon in which each carbon is already bound to four other atoms. Alkanes are saturated hydrocarbons.

**SINGLE BOND:** A form of bonding in which two atoms share one pair of valence electrons. Carbon is also capable of double bonds and triple bonds.

**SUBSTITUENTS:** Branches of alkanes, named by taking the name of an alkane and replacing the suffix with yl—for example, methyl, ethyl, and so on.

**TETRAVALENT:** Capable of bonding to four other elements.

**TRIPLE BOND:** A form of bonding in which two atoms share three pairs of valence electrons. Carbon is also capable of single bonds and double bonds.

**UNSATURATED:** A term describing a hydrocarbon in which the carbons involved in a multiple bond (a double bond or triple bond) are free to bond with other atoms. Alkenes and alkynes are both unsaturated.

**VALENCE ELECTRONS:** Electrons that occupy the highest principal energy level in an atom. These are the electrons involved in chemical bonding.

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# POLYMERS

## CONCEPT

Formed from hydrocarbons, hydrocarbon derivatives, or sometimes from silicon, polymers are the basis not only for numerous natural materials, but also for most of the synthetic plastics that one encounters every day. Polymers consist of extremely large, chain-like molecules that are, in turn, made up of numerous smaller, repeating units called monomers. Chains of polymers can be compared to paper clips linked together in long strands, and sometimes cross-linked to form even more durable chains. Polymers can be composed of more than one type of monomer, and they can be altered in other ways. Likewise they are created by two different chemical processes, and thus are divided into addition and condensation polymers. Among the natural polymers are wool, hair, silk, rubber, and sand, while the many synthetic polymers include nylon, synthetic rubber, Teflon, Formica, Dacron, and so forth. It is very difficult to spend a day without encountering a natural polymer—even if hair is removed from the list—but in the twenty-first century, it is probably even harder to avoid synthetic polymers, which have collectively revolutionized human existence.

## HOW IT WORKS

### Polymers of Silicon and Carbon

Polymers can be defined as large, typically chain-like molecules composed of numerous smaller, repeating units known as monomers. There are numerous varieties of monomers, and since these can be combined in different ways to form polymers, there are even more of the latter.

The name "polymer" does not, in itself, define the materials that polymers contain. A handful of polymers, such as natural sand or synthetic silicone oils and rubbers, are built around silicon. However, the vast majority of polymers center around an element that occupies a position just above silicon on the periodic table: carbon.

The similarities between these two are so great, in fact, that some chemists speak of Group 4 (Group 14 in the IUPAC system) on the periodic table as the "carbon family." Both carbon and silicon have the ability to form long chains of atoms that include bonds with other elements. The heavier elements of this "family," however (most notably lead), are made of atoms too big to form the vast array of chains and compounds for which silicon and carbon are noted.

Indeed, not even silicon—though it is at the center of an enormous range of inorganic compounds—can compete with carbon in its ability to form arrangements of atoms in various shapes and sizes, and hence to participate in an almost limitless array of compounds. The reason, in large part, is that carbon atoms are much smaller than those of silicon, and thus can bond to one another and still leave room for other bonds.

Carbon is such an important element that an entire essay in this book is devoted to it, while a second essay discusses organic chemistry, the study of compounds containing carbon. In the present context, there will be occasional references to non-carbon (that is, silicon) polymers, but the majority of our attention will be devoted to hydrocarbon and hydrocarbon-derivative polymers, which most of us know simply as "plastics."



COTTON IS AN EXAMPLE OF A NATURAL POLYMER. *(Carl Corey/Corbis. Reproduced by permission.)*

## ORGANIC CHEMISTRY

As explained in the essay on Organic Chemistry, chemists once defined the term "organic" as relating only to living organisms; the materials that make them up; materials derived from them; and substances that come from formerly living organisms. This definition, which more or less represents the everyday meaning of "organic," includes a huge array of life forms and materials: humans, all other animals, insects, plants, microorganisms, and viruses; all substances that make up their structures (for example, blood, DNA, and proteins); all products that come from them (a list diverse enough to encompass everything from urine to honey); and all materials derived from the bodies of organisms that were once alive (paper, for instance, or fossil fuels).

As broad as this definition is, it is not broad enough to represent all the substances addressed by organic chemistry—the study of carbon, its compounds, and their properties. All living or once-living things do contain carbon; however, organic chemistry is also concerned with carbon-containing materials—for instance, the synthetic plastics we will discuss in this essay—that have never been part of a living organism.

It should be noted that while organic chemistry involves only materials that contain carbon, carbon itself is found in other compounds not considered organic: oxides such as carbon dioxide and monoxide, as well as carbonates, most notably calcium carbonate or limestone. In other words, as broad as the meaning of "organic" is, it still does not encompass all substances containing carbon.

## HYDROCARBONS

As for hydrocarbons, these are chemical compounds whose molecules are made up of nothing but carbon and hydrogen atoms. Every molecule in a hydrocarbon is built upon a "skeleton" of carbon atoms, either in closed rings or in long chains, which are sometimes straight and sometimes branched.

Theoretically, there is no limit to the number of possible hydrocarbons: not only does carbon form itself into seemingly limitless molecular shapes, but hydrogen is a particularly good partner. It is the smallest atom of any element on the periodic table, and therefore it can bond to one of carbon's four valence electrons without getting in the way of the other three.

There are many, many varieties of hydrocarbon, classified generally as aliphatic hydrocarbons (alkanes, alkenes, and alkynes) and aromatic hydrocarbons, the latter being those that con-



Modern appliances contain numerous examples of synthetic polymers, from the flooring to the countertops to virtually all appliances. *(Scott Roper/Corbis. Reproduced by permission.)*

tain a benzene ring. By means of a basic alteration in the shape or structure of a hydrocarbon, it is possible to create new varieties. Thus, as noted above, the number of possible hydrocarbons is essentially unlimited.

Certain hydrocarbons are particularly useful, one example being petroleum, a term that refers to a wide array of hydrocarbons. Among these is an alkane that goes by the name of octane ($C_8H_{18}$), a preferred ingredient in gasoline. Hydrocarbons can be combined with various functional groups (an atom or group of atoms whose presence identifies a specific family of compounds) to form hydrocarbon derivatives such as alcohols and esters.

## REAL-LIFE APPLICATIONS

### Types of Polymers and Polymerization

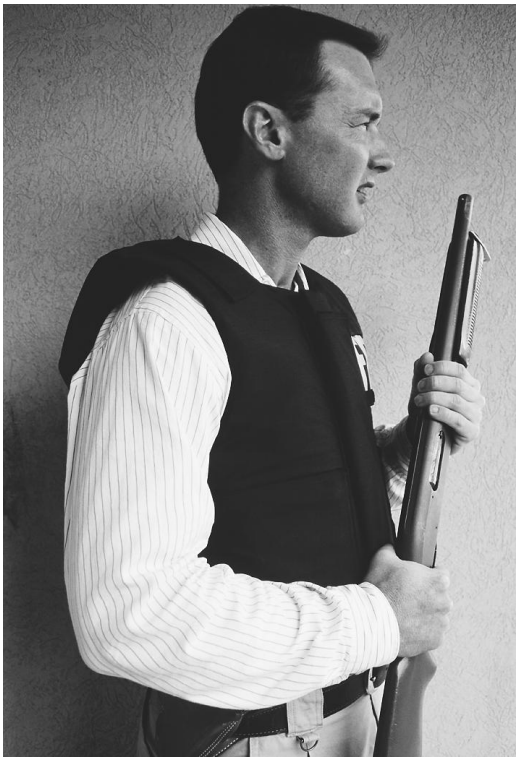
Many polymers exist in nature. Among these are silk, cotton, starch, sand, and asbestos, as well as the incredibly complex polymers known as RNA (ribonucleic acid) and DNA (deoxyribonucleic acid), which hold genetic codes. The polymers discussed in this essay, however, are primarily of the synthetic kind. Artificial polymers include such plastics (defined below) as polyethylene, styrofoam, and Saran wrap; fibers such as nylon, Dacron (polyester), and rayon; and other materials such as Formica, Teflon, and PVC pipe.

As noted earlier, most polymers are formed from monomers either of hydrocarbon or hydrocarbon derivatives. The most basic synthetic monomer is ethylene ($C_2H_4$), a name whose -ene ending identifies it as an alkene, a hydrocarbon formed by double bonds between carbon atoms. Another alkene hydrocarbon monomer is butadiene, whose formula is $C_4H_6$. This is an example of the fact that the formula of a compound does not tell the whole story: on paper, the difference between these two appears to be merely a matter of two extra atoms each of carbon and hydrogen. In fact, butadiene's structure is much more complex.

Still more complex is styrene, which includes a benzene ring. Several other monomers involve other elements: chloride, in vinyl chloride; nitrogen, in acrylonitrile; and fluorine, in tetrafluoroethylene. It is not necessary, in the present context, to keep track of all of these substances, which in any case represent just some of the more prominent among a wide variety of synthetic monomers. A good high-school or college chemistry textbook (either general chemistry or organic chemistry) should provide structural representations of these common monomers. Such representations will show, for instance, the vast differences between purely hydrocarbon monomers such as ethylene, propylene, styrene, and butadiene.

When combined into polymers, the monomers above form the basis for a variety of useful and familiar products. Once the carbon double bonds in tetrafluoroethylene ($C_2F_4$) are broken, they form the polymer known as Teflon, used in the coatings of cooking utensils, as well as in electrical insulation and bearings. Vinyl chloride breaks its double bonds to form polyvinyl chloride, better known as PVC, a material used for everything from plumbing pipe to toys to Saran wrap. Styrene, after breaking its double bonds, forms polystyrene, used in containers and thermal insulation.

**POLYMERIZATION.** Note that several times in the preceding paragraph, there was a reference to the breaking of carbon double bonds. This is often part of one variety of polymerization, the process whereby monomers join to form polymers. If monomers of a single type join, the resulting polymer is called a homopolymer, but if the polymer consists of more than one type of monomer, it is known as a copolymer. This joining may take place by one of two processes. The first of these, addition polymerization, is fairly simple: monomers add themselves to one another, usually breaking double bonds in the process. This results in the creation of a polymer and no other products.



A SYNTHETIC POLYMER KNOWN AS KEVLAR IS USED IN THE CONSTRUCTION OF BULLETPROOF VESTS FOR LAW-ENFORCEMENT OFFICERS. *(Anna Clopet/Corbis. Reproduced by permission.)*

Much more complex is the process known as condensation polymerization, in which a small molecule called a dimer is formed as monomers join. The specifics are too complicated to discuss in any detail, but a few things can be said here about condensation polymerization. The monomers in condensation polymerization must be bifunctional, meaning that they have a functional group at each end. When characteristic structures at the ends of the monomers react to one another by forming a bond, they create a dimer, which splits off from the polymer. The products of condensation polymerization are thus not only the polymer itself, but also a dimer, which may be water, hydrochloric acid (HCl), or some other substance.

## A Plastic World

**A DAY IN THE LIFE.** Though "plastic" has a number of meanings in everyday life,

and in society at large (as we shall see), the scientific definition is much more specific. Plastics are materials, usually organic, that can be caused to flow under certain conditions of heat and pressure, and thus to assume a desired shape when the pressure and temperature conditions are withdrawn. Most plastics are made of polymers.

Every day, a person comes into contact with dozens, if not hundreds, of plastics and polymers. Consider a day in the life of a hypothetical teenage girl. She gets up in the morning, brushes her teeth with a toothbrush made of nylon, then opens a shower door—which is likely to be plastic rather than glass—and steps into a molded plastic shower or bathtub. When she gets out of the shower, she dries off with a towel containing a polymer such as rayon, perhaps while standing on tile that contains plastics, or polymers.

She puts on makeup (containing polymers) that comes in plastic containers, and later blow-dries her hair with a handheld hair dryer made of insulated plastic. Her clothes, too, are likely to contain synthetic materials made of polymers. When she goes to the kitchen for breakfast, she will almost certainly walk on flooring with a plastic coating. The countertops may be of formica, a condensation polymer, while it is likely that virtually every appliance in the room will contain plastic. If she opens the refrigerator to get out a milk container, it too will be made of plastic, or of paper with a thin plastic coating. Much of the packaging on the food she eats, as well as sandwich bags and containers for storing food, is also made of plastic.

And so it goes throughout the day. The phone she uses to call a friend, the computer she sits at to check her e-mail, and the stereo in her room all contain electrical components housed in plastic. If she goes to the gym, she may work out in Gore-tex, a fabric containing a very thin layer of plastic with billions of tiny pores, so that it lets through water vapor (that is, perspiration) without allowing the passage of liquid water. On the way to the health club, she will ride in a car that contains numerous plastic molds in the steering wheel and dashboard. If she plays a compact disc—itself a thin wafer of plastic coated with metal—she will pull it out of a plastic jewel case. Finally, at night, chances are she will sleep in sheets, and with a pillow, containing synthetic polymers.

**A SILENT REVOLUTION.** The scenario described above—a world surrounded by polymers, plastics, and synthetic materials—represents a very recent phenomenon. "Before the 1930s," wrote John Steele Gordon in an article about plastics for American Heritage, "almost everything people saw or handled was made of materials that had been around since ancient times: wood, stone, metal, and animal and plant fibers." All of that changed in the era just before World War II, thanks in large part to a brilliant young American chemist named Wallace Carothers (1896-1937).

By developing nylon for E. I. du Pont de Nemours and Company (known simply as "DuPont" or "du Pont"), Carothers and his colleagues virtually laid the foundation for modern polymer chemistry—a field that employs more chemists than any other. These men created what Gordon called a "materials revolution" by introducing the world to polymers and plastics, which are typically made of polymers.

Yet as Gordon went on to note, "It has been a curiously silent revolution.... When we think of the scientific triumphs of [the twentieth century], we think of nuclear physics, medicine, space exploration, and the computer. But all these developments would have been much impeded, in some cases impossible, without... plastics. And yet 'plastic' remains, as often as not, a term of opprobrium."

**AMBIVALENCE TOWARD PLASTICS.** Gordon was alluding to a cultural attitude discussed in the essay on Organic Chemistry: the association of plastics, a physical material developed by chemical processes, with the condition—spiritual, moral, and intellectual—of being "plastic" or inauthentic. This was symbolized in a famous piece of dialogue about plastics from the 1967 movie *The Graduate*, in which a nonplussed Ben Braddock (Dustin Hoffman) listens as one of his parents' friends advises him to invest his future in plastics. As Gordon noted, "however intergenerationally challenged that half-drunk friend of Dustin Hoffman's parents may have been... he was right about the importance of the materials revolution in the twentieth century."

One aspect of society's ambivalence over plastics relates to very genuine concerns about the environment. Most synthetic polymers are made from petroleum, a nonrenewable resource;

but this is not the greatest environmental danger that plastics present. Most plastics are not biodegradable: though made of organic materials, they do not contain materials that will decompose and eventually return to the ground. Nor is there anything in plastics to attract microorganisms, which, by assisting in the decomposition of organic materials, help to facilitate the balance of decay and regeneration necessary for life on Earth.

Efforts are underway among organic chemists in the research laboratories of corporations and other institutions to develop biodegradable plastics that will speed up the decomposition of materials in the polymers—a process that normally takes decades. Until such replacement polymers are developed, however, the most environmentally friendly solution to the problem of plastics is recycling. Today only about 1% of plastics are recycled, while the rest goes into waste dumps, where they account for 30% of the volume of trash.

Long before environmental concerns came to the forefront, however, people had begun almost to fear plastics as a depersonalizing aspect of modern life. It seemed that in a given day, a person touched fewer and fewer things that came directly from the natural environment: the "wood, stone, metal, and animal and plant fibers" to which Gordon alluded. Plastics seemed to have made human life emptier; yet the truth of the matter—including the fact that plastics add more than they take away from the landscape of our world—is much more complex.

## The Plastics Revolution

Though the introduction of plastics is typically associated with the twentieth century, in fact the "materials revolution" surrounding plastics began in 1865. That was the year when English chemist Alexander Parkes (1813-1890) produced the first plastic material, celluloid. Parkes could have become a rich man from his invention, but he was not a successful marketer. Instead, the man who enjoyed the first commercial success in plastics was—not surprisingly—an American, inventor John Wesley Hyatt (1837-1920).

Responding to a contest in which a billiard-ball manufacturer offered $10,000 to anyone who could create a substitute for ivory, which was extremely costly, Hyatt turned to Parkes's celluloid. Actually, Parkes had given his creation—developed from cellulose, a substance found in the cell walls of plants—a much less appealing name, "Parkesine." Hyatt, who used celluloid to make smooth, hard, round billiard balls (thereby winning the contest) took out a patent for the process involved in making the material he had dubbed "Celluloid," with a capital C.

Though the Celluloid made by Hyatt's process was flammable (as was Parkesine), it proved highly successful as a product when he introduced it in 1869. He marketed it successfully for use in items such as combs and baby rattles, and Celluloid sales received a powerful boost after photography pioneer George Eastman (1854-1932) chose the material for use in the development of film. Eventually, Celluloid would be applied in motion-picture film, and even today, the adjective "celluloid" is sometimes used in relation to the movies. Actually, Celluloid (which can be explosive in large quantities) was phased out in favor of "safety film," or cellulose acetate, beginning in 1924.

Two important developments in the creation of synthetic polymers occurred at the turn of the century. One was the development of Galalith, an ivory-like substance made from formaldehyde and milk, by German chemist Adolf Spitteler. An even more important innovation happened in 1907, when Belgian-American chemist Leo Baekeland (1863-1944) introduced Bakelite. The latter, created in a reaction between phenol and formaldehyde, was a hard, black plastic that proved an excellent insulator. It soon found application in making telephones and household appliances, and by the 1920s, chemists had figured out how to add pigments to Bakelite, thus introducing the public to colored plastics.

**SYNTHETIC RUBBER.** Throughout these developments, chemists had only a vague understanding of polymers, but by the 1930s, they had come to accept the model of polymers as large, flexible, chain-like molecules. One of the most promising figures in the emerging field of polymer chemistry was Carothers, who in 1926 left a teaching post at Harvard University to accept a position as director of the polymer research laboratory at DuPont.

Among the first problems Carothers tackled was the development of synthetic rubber. Natural rubber had been known for many centuries when English chemist Joseph Priestley (1733-1804) gave it its name because he used it to rub

out pencil marks. In 1839, American inventor Charles Goodyear (1800-1860) accidentally discovered a method for making rubber more durable, after he spilled a mixture of rubber and sulfur onto a hot stove. Rather than melting, the rubber bonded with the sulfur to form a much stronger but still elastic product, and Goodyear soon patented this process under the name vulcanization.

Natural rubber, nonetheless, had many undesirable properties, and hence DuPont put Carothers to the task of developing a substitute. The result was neoprene, which he created by adding a chlorine atom to an acetylene derivative. Neoprene was stronger, more durable, and less likely to become brittle in cold weather than natural rubber. It would later prove an enormous boost to the Allied war effort, after the Japanese seized the rubber plantations of Southeast Asia in 1941.

**NYLON.** Had neoprene, which Carothers developed in 1931, been the extent of his achievements, he would still be remembered by science historians. However, his greatest creation still lay ahead of him. Studying the properties of silk, he became convinced that he could develop a more durable compound that could replicate the properties of silk at a much lower cost.

Carothers was not alone in his efforts, as Gordon showed in his account of events at the DuPont laboratories:

One day, an assistant, Julian Hill, noticed that when he stuck a glass stirring rod into a gooey mass at the bottom of a beaker the researchers had been investigating, he could draw out threads from it, the polymers forming spontaneously as he pulled. When Carothers was absent one day, Hill and his colleagues decided to see how far they could go with pulling threads out of goo by having one man hold the beaker while another ran down the hall with the glass rod. A very long, silk-like thread was produced.

Realizing what they had on their hands, DuPont devoted $27 million to the research efforts of Carothers and his associates at the lab, and in 1937, Carothers presented his boss with the results, saying "Here is your synthetic textile fabric." DuPont introduced the material, nylon, to the American public the following year with one of the most famous advertising campaigns of all time: "Better Things for Better Living Through Chemistry."

The product got an additional boost through exposure at the 1939 World's Fair. When DuPont put 4,000 pairs of nylon stockings on the market, they sold in a matter of hours. A few months later, four million pairs sold in New York City in a single day. Women stood in line to buy stockings of nylon, a much better (and less expensive) material for that purpose than silk—but they did not have long to enjoy it. During World War II, all nylon went into making war materials such as parachutes, and nylon did not become commercially available again until 1946.

As Gordon noted, Carothers would surely have won the Nobel Prize in chemistry for his work—"but Nobel prizes go only to living recipients...." Carothers had married in 1936, and by early 1937, his wife Helen was pregnant. (Presumably, he was unaware of the fact that he was about to become a father.) Though highly enthusiastic about his work, Carothers was always shy and withdrawn, and in Gordon's words, "he had few outlets other than work." He was, however, a talented singer, as was his closest sibling, Isobel, a radio celebrity. Her death in January 1937 sent him into a bout of depression, and on April 29, he killed himself with a dose of cyanide. Seven months later, on November 27, Helen gave birth to a daughter, Jane.

**HOW PLASTICS HAVE ENHANCED LIFE.** Despite his tragic end, Carothers had brought much good to the world by sparking enormous interest in polymer research and plastics. Over the years that followed, polymer chemists developed numerous products that had applications in a wide variety of areas. Some, such as polyester—a copolymer of terephthalic acid and ethylene—seemed to fit the idea of "plastics" as ugly, inauthentic, and even dehumanizing. During the 1970s, clothes of polyester became fashionable, but by the early 1980s, there was a public backlash against synthetics, and in favor of natural materials.

Yet even as the public rejected synthetic fabrics for everyday wear, Gore-tex and other synthetics became popular for outdoor and workout clothing. At the same time, the polyester that many regarded as grotesque when used in clothing was applied in making safer beverage bottles. The American Plastics Council dramatized this in a 1990s commercial that showed a few seconds in the life of a mother. Her child takes a soft-

## KEY TERMS

**ADDITION POLYMERIZATION:** A form of polymerization in which monomers having at least one double bond or triple bond simply add to one another, forming a polymer and no other products. Compare to condensation polymerization.

**ALKENES:** Hydrocarbons that contain double bonds.

**COPOLYMER:** A polymer composed of more than one type of monomer.

**DIMER:** A molecule formed by the joining of two monomers.

**DOUBLE BOND:** A form of bonding in which two atoms share two pairs of valence electrons. Carbon is noted for its ability to form double bonds, as for instance in many hydrocarbons.

**FUNCTIONAL GROUPS:** An atom or group of atoms whose presence identifies a specific family of compounds. When combined with hydrocarbons, various functional groups form hydrocarbon derivatives.

**HOMOPOLYMER:** A polymer that consists of only one type of monomer.

**HYDROCARBON:** Any chemical compound whose molecules are made up of nothing but carbon and hydrogen atoms.

**HYDROCARBON DERIVATIVES:** Families of compounds formed by the joining of hydrocarbons with various functional groups.

**MONOMERS:** Small, individual subunits, often built of hydrocarbons, that join together to form polymers.

**ORGANIC:** A term referring to any compound that contains carbon, except for oxides such as carbon dioxide, or carbonates such as calcium carbonate (i.e., limestone).

**ORGANIC CHEMISTRY:** The study of carbon, its compounds, and their properties.

**PLASTICS:** Materials, usually organic, that can be caused to flow under certain conditions of heat and pressure, and thus to assume a desired shape when the pressure and temperature conditions are withdrawn. Plastics are usually made up of polymers.

**POLYMERIZATION:** The process whereby monomers join to form polymers.

**POLYMERS:** Large, typically chain-like molecules composed of numerous smaller, repeating units known as monomers.

**VALENCE ELECTRONS:** Electrons that occupy the highest principal energy level in an atom. These are the electrons involved in chemical bonding.

drink bottle out of the refrigerator and drops it, and the mother cringes at what she thinks she is about to see next: glass shattering around her child. But she is remembering the way things were when she was a child, when soft drinks still came in glass bottles: instead, the plastic bottle bounces harmlessly.

Of course, such dramatizations may seem a bit self-serving to critics of plastic, but the fact remains that plastics enhance—and in some cases even preserve—life. Kevlar, for instance, enhances life when it is used in making canoes for recreation; when used to make a bulletproof vest, it can save the life of a law-enforcement officer. Mylar, a form of polyester, enhances life

when used to make a durable child's balloon—but this highly nonreactive material also saves lives when it is applied to make replacement human blood vessels, or even replacement skin for burn victims.

## RECYCLING

As mentioned above, plastics—for all their benefits—do pose a genuine environmental threat, due to the fact that the polymers break down much more slowly than materials from living organisms. Hence the need not only to develop biodegradable plastics, but also to work on more effective means of recycling.

One of the challenges in the recycling arena is the fact that plastics come in a variety of grades. Different catalysts are used to make polymers that possess different properties, with varying sizes of molecules, and in chains that may be linear, branched, or cross-linked. Long chains of 10,000 or more monomers can be packed closely to form a hard, tough plastic known as high-density polyethylene or HDPE, used for bottles containing milk, soft drinks, liquid soap, and other products. On the other hand, shorter, branched chains of about 500 ethylene monomers each produce a much less dense plastic, low-density polyethylene or LDPE. This is used for plastic food or garment bags, spray bottles, and so forth. There are other grades of plastic as well.

In some forms of recycling, plastics of all varieties are melted down together to yield a cheap, low-grade product known as "plastic lumber," used in materials such as landscaping timbers, or in making park benches. In order to achieve higher-grade recycled plastics, the materials need to be separated, and to facilitate this, recycling codes have been developed. Many plastic materials sold today are stamped with a recycling code number between 1 and 6, identifying specific varieties of plastic. These can be melted or ground according to type at recycling centers, and reprocessed to make more plastics of the same grade.

To meet the environmental challenges posed by plastics, polymer chemists continue to research new methods of recycling, and of using recycled plastic. One impediment to recycling, however, is the fact that most state and local governments do not make it convenient, for instance by arranging trash pickup for items that have been separated into plastic, paper, and glass products. Though ideally private recycling centers would be preferable to government-operated recycling, few private companies have the financial resources to make recycling of plastics and other materials practical.

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