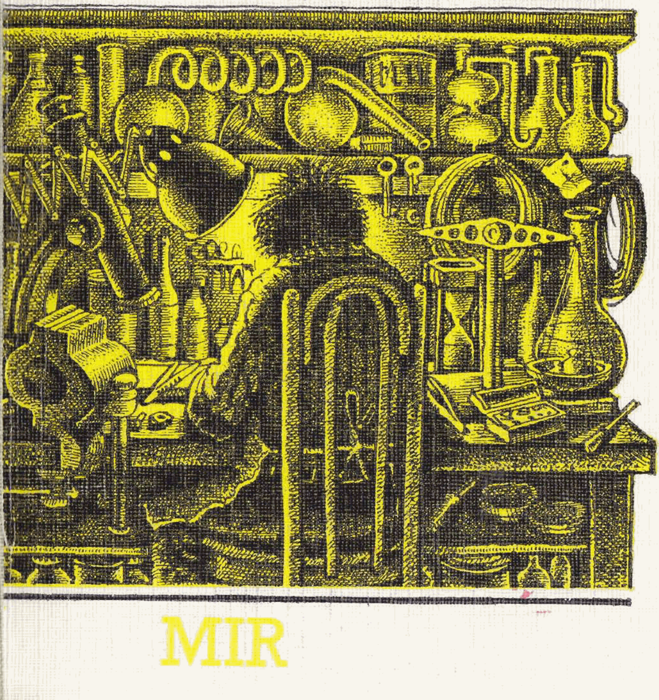
SCIENCE FOR EVERYONE

PHYSICS IN YOUR KITCHEN LAB



MIR

Опыты в домашней лаборатории

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Physics in Your Kitchen Lab

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To Georgii Ivanovich Kosourov

Editor's Note

Physics is an experimental science since it studies the fundamental laws of nature by direct experimentation. The experimenter asks questions of nature in any experimental work, but only correctly formulated questions are answered. This means that unless a physical experiment is set up correctly, the experimenter will not get the desired results. An experimenter's skill, therefore, depends on his ability to formulate experiments correctly. The experimental physics is a fascinating science, which enables us to understand, explain and, sometimes, even discover new phenomena in nature. The first step in becoming an accomplished physicist is mastering of the techniques of physical experimentation.

Modern experimental physics uses very sophisticated and expensive apparatus, housed, for the most part, in large research institutes and laboratories where many of the readers of this book may one day conduct their own original research. Until then, however, the engaging experiments described in this book can be performed right at home. Most of the experiments included here were first published separately in the journal *Kvant*.

Just as "a picture is worth a thousand words", an experiment once performed is worth a thousand descriptions of one. It is recommended, therefore, that readers perform the experiments described themselves. The means for this are readily available, and it should soon become obvious that experimentation is a captivating pastime. The experiments presented here need not be confining; they may be varied and expanded, providing, in this way, an opportunity for real scientific investigation.

The book is dedicated to Georgii Ivanovich Kosourov, one of the founding fathers of *Kvant*. Kosourov, who edited the experimental section of the journal in its first year of publication, has contributed several very interesting articles to this collection. Among the other authors of this book are a number of famous physicists, as well as young researchers just beginning their careers. We hope this book will fascinate not only students already interested in physics who intend to make it their lifework but also the friends to whom they demonstrate the experiments in a laboratory made right at home.

A Demonstration of Weightlessness

by A. Dozorov

The weightless state is achieved in free flight. A satellite in orbit, a free falling stone, and a man during a jump are all in a state of weightlessness. A weight suspended from a string weighs nothing in a free fall and, therefore, does not pull on the string. It is easy to make a device that will let you "observe" weightlessness.

Figure 1 depicts such a device schematically. In its 'normal' state, weight *G* pulls the string

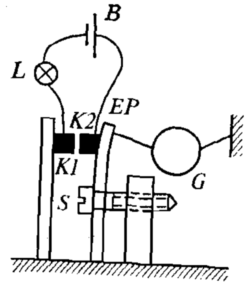


Fig. 1

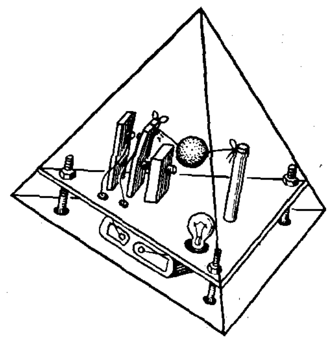


Fig. 2

taut, and elastic plate *EP* bends, breaking the contact between terminals *K*1 and *K*2 of the circuit. Naturally, lamp L, connected to the circuit, does not light up in this case. If the entire device is tossed into the air, however, weight G becomes weightless and does not tighten the string. The elastic plate straightens out and the terminals connect, which switches on the lamp. The lamp is lit only when the device is in a weightless state. Note that this state is achieved both when the device is thrown up and as it returns to the ground.

The adjustment screw S makes it possible to place the terminals so that they have a small clearance when the device is stationary. The device is fastened to the inside of a transparent box, as shown in Fig. 2.

A little practical advice about construction. In order to provide for the use of a large-cell (flat) battery or a small one-cell battery, reserve space for the larger battery. Access to the battery compartment should be facilitated since battery may have to be replaced frequently. The battery can be secured to the outer surface of the device, and two holes for connecting wires should be provided in the casing.

Any thin elastic metal strip can be used as an elastic plate, even one half of a safety razor blade (after fastening the blade to the stand, you will see where to connect the string for the weight).

The design can be simplified further, if the adjustment screw and terminal $K1$ are combined and the plate functions as terminal $K2$ (Fig. 3). Figure 4 shows a design that has no adjustment screw at all. If you think a little, you can probably come up with an even simpler design.

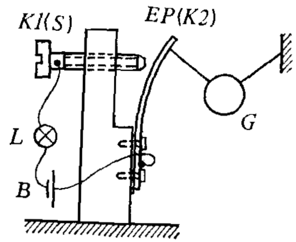


Fig. 3

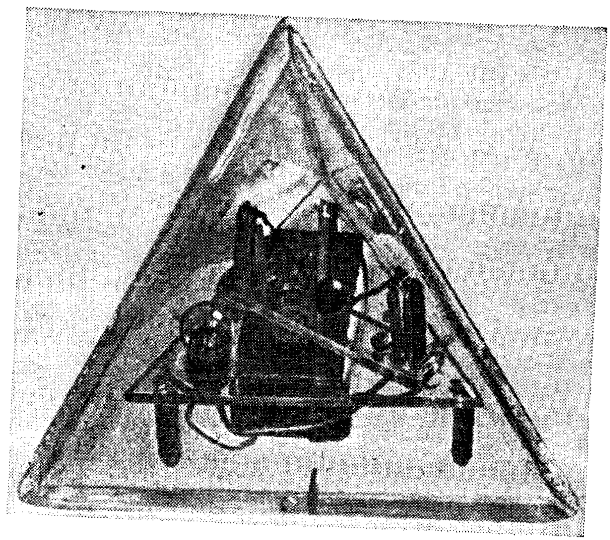


Fig. 4

A Cartesian Diver

by A. Vilenkin

A toy ship made of paper will float easily, but if the paper gets soaked, the ship sinks. When the paper is dry, it traps air between its bell and the surface of the water. If the bell gets soaked and begins to disintegrate, the air escapes the bell and the ship sinks. But is it possible to make a ship whose bell alternately keeps or releases air, making the ship float or sink as we wish? It is, indeed. The great French scholar and philosopher René Descartes was the first to make such a toy, now commonly called the 'Cartesian Diver' (from Cartesius, the Latin spelling of Descartes). Descartes' toy resembles our paper ship except that the 'Diver' compresses and expands the air instead of letting it in and out.

A design of the 'Diver' is shown in Fig. 5. Take a milk bottle, a small medicine bottle and a rubber balloon (the balloon will have to be spoiled). Fill the milk bottle with water almost to its neck. Then lower the medicine bottle into the water, neck down. Tilt the medicine bottle slightly to let some of the water in. The amount of water inside the smaller bottle should be regulated so that the bottle floats on the surface and a slight push makes it sink (a straw can be used to blow air into the bottle while it is underwater). Once the medicine bottle is floating properly, seal the milk bottle with a piece of rubber cut from the balloon and fastened to the bottle with a thread wound around the neck.

Press down the piece of rubber, and the 'Diver' will sink. Release it, and the 'Diver' will rise.

This is because the air inside the milk bottle is compressed when the piece of rubber is pushed in. The pressure forces water into the medicine

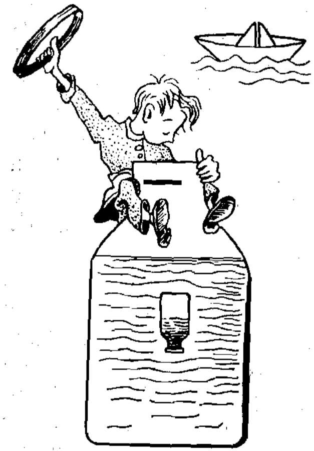


Fig. 5

bottle, which becomes heavier and sinks. As soon as the pressure is released, the air in the medicine bottle forces the extra water out, and the 'Diver' floats up.

An Automatic Siphon

by V. Mayer and N. Nazarov

Most of you probably studied the workings of the siphon, the simplest device for pumping liquids, while still in grade school. The famous American physicist Robert Wood is said to have begun his scientific career when still a boy with just such a siphon. This is how W. Seabrook described that first experiment in his book about Robert Wood. He wrote that there was an elevation over a foot high around a puddle, and everybody knew that water would not flow uphill. Rob laid a hose on the ground and told one of the boys to seal its end with his finger. Then he started filling the hose with water until it was full. Already a born demonstrator at that age, Rob, instead of leaving his end of the hose on the ground, let it dangle over a high fence which separated the road from the ditch. Water flowed through the siphon. This was apparently Wood's first public scientific victory.

The conventional siphon is so simple that almost no improvement in its design seems possible. Perhaps its only disadvantage is that it is necessary to force the air from bends in the siphon prior to operation. Yet even this problem was solved, thanks to human ingenuity. Once inventors had understood the shortcoming in the design, they removed it by the simplest possible means!

To make an automatic siphon*, you will need a glass tube whose length is about 60 cm and whose inner diameter is 3-4 mm. Bend the tube over a flame so that it has two sections, one of which is about 25 cm long (Fig. 6). Carefully cut a small hole (*1*) in the shorter arm about 33-35 mm from its end with the edge of a needle file (wet the file first). The area of the hole should not be more than 0.5-1 mm^2. Take a ping-pong

* This version of the automatic siphon, invented by S.D. Platonov, was described in *Zavodskaya Laboratoriya*, 4, No. 6 (1935) (in Russian).

ball, and make a small hole in it which is then reamed with the file until the tube can be pushed into the ball and is held there tightly. Push the

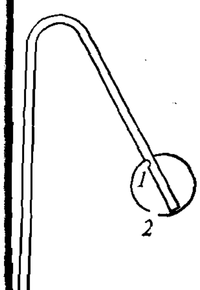


Fig. 6

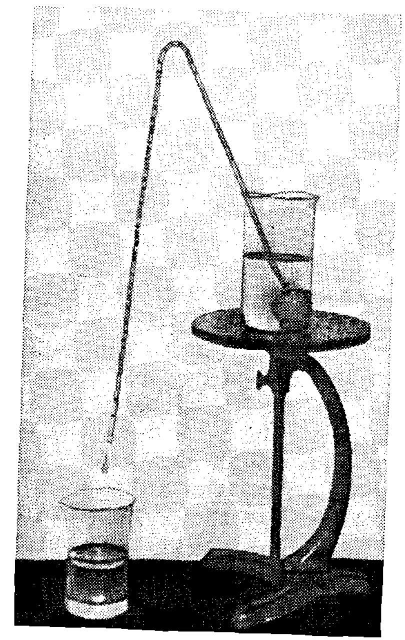


Fig. 7

tube into the hole until its end nearly touches the side of the ball opposite the hole (Fig. 6). The tube should fit tightly in the opening. If the hole is too large, fill the gap with plasticine. Make another hole (*2*) close to the end of the tube inside the ball. Its initial diameter should be about 1 mm.

Quickly lower the arm of the siphon with the ball at the end into a glass of water. The tube will fill almost immediately with a rising column of water broken by a series of air bubbles. When the water reaches the bend, it will move down the second arm of the siphon (Fig. 7), and in a few moments a continuous stream of water will begin to flow from the end of the tube!

If the experiment is unsuccessful at first, simply adjust the siphon slightly. The correct operation of the automatic siphon depends on the appropriate choice of diameters of the holes in the tube and the ball. Faulty positioning of the glass tube and the ball or an inadequate seal between the tube and the ball may also spoil the siphon operation. The second hole in the ball can be gradually enlarged with a needle file to improve the performance of the siphon. As soon as the siphon is operating satisfactorily, glue the ball to the tube.

How does the automatic siphon work? Look at Fig. 6 again. When the ball is lowered into the glass, water floods simultaneously into opening *2* and into the open end of the glass tube. Water rises in the tube at a faster rate than in the ball. The water rising to opening *1* in the wall of the tube seals the tube. As the ball floods with water, the air pressure inside it rises. When equilibrium is reached, a small air bubble is forced through the opening *1*. The bubble cuts off a small column of water and carries it upward. The water that follows reseals opening *1*, and the compressed air forces another air bubble into the tube, cutting off another portion of water. Thus, the section of tube with the ball has an air/water mixture whose density is lower than that of water. Under hydrostatic pressure this mixture rises to the bend and flows down the second arm of the tube. When the ball is completely filled with water, pressure creates a continuous flow of water and the siphon begins to operate.

EXERCISES

1. Show experimentally that water floods the ball at a slower rate than the tube. Explain why.
2. To be certain that the explanation of the operation of the siphon is correct, replace the opaque ball with a small glass bottle with a rubber stopper. The design of the setup with the bottle should be an exact replica of the original. The glass tube should go through the rubber stopper. Since the bottle is transparent, you will be able to see the air/water mixture forming in the tube.
3. Determine whether the rise of the column of water depends on the water depth of the ball.
4. Make an automatic siphon by replacing the glass tube with a rubber hose.

Vortex Rings

by R. W. Wood

In the course of some experiments preparatory to a lecture on vortex rings I have introduced certain modifications which may be of interest to teachers and students of science.

The classic vortex-box is too well known to require much description. Our apparatus, which is rather larger than those in common use, is a pine box measuring about a metre each way,

* *Nature*, February 28, 1901, pp. 418-420.

with a circular hole 25 cms in diameter in one end. Two pieces of heavy rubber tubing are stretched diagonally across the opposite or open end, which is then covered with black enamel cloth tacked on rather loosely. The object of the rubber chords is to give the recoil necessary after the expulsion of a ring to prepare the box for a second discharge. Such a box will project air vortices of great power, the slap of the ring

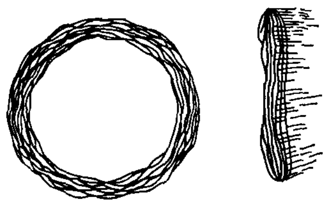


Fig. 8

against the brick wall of the lecture hall being distinctly audible resembling the sound of a flip with a towel. An audience can be given a vivid idea of the quasi-rigidity of a fluid in rotation by projecting these invisible rings in rapid succession into the auditorium, the impact of the ring on the face reminding one of a blow with a compact tuft of cotton.

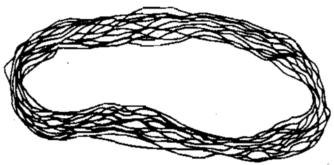
For rendering rings visible I have found that by far the best results can be obtained by conducting ammonia and hydrochloric acid gases into the box through rubber tubes leading to two flasks in which NH_4OH and HCl are boiling. Photographs of large rings made in this way are reproduced in Fig. 8, the side view being particularly interesting, showing the comet-like tail formed by the stripping off of the outer portions of the

ring by atmospheric friction as it moves forward.

The power of the air-rings can be shown by directing them against a flat pasteboard box, stood on end at some distance from the vortex apparatus, the box being at once overturned or even driven off on to the floor. A large cluster of burning gas jets can be extinguished by the impact of a ring.

For showing the elasticity of the rings by bouncing one off the other, I find that the best plan is to drive two in rapid succession from the box, the second being projected with a slightly greater velocity than the first, all experiments that I have made with twin boxes having yielded unsatisfactory results.

Though the large vortices obtained with an apparatus of this description are most suitable for lecture purposes, I find that much more beautiful and symmetrical rings can be made with tobacco smoke blown from a paper or glass tube about 2.5 cm in diameter. It is necessary to practice a little to learn just the nature and strength of the most suitable puff. Rings blown in this way in still air near a lamp or in full sunlight, when viewed laterally, show the spiral stream lines in a most beautiful manner. I have succeeded in photographing one of these rings in the following way. An instantaneous drop shutter was fitted to the door of a dark room and an arclamp focussed on its aperture by means of a large concave mirror. The shutter was a simple affair, merely an aluminium slide operated with an elastic band, giving an exposure of 1/300 of a second. A photographic plate was set on edge in the dark room in such a position that it would be illuminated by the divergent beam coming from the image of the arc when the shutter was opened. A ruby lamp was placed in front of the sensitive film. As soon as a good ring, symm trical in form and not moving too fast, was seen to be in front of the plate, a string leading to the shutter was pulled and the plate illuminated with a dazzling flash. The ring casts a perfectly sharp shadow owing to the small size and distance of



the source of light; the resulting picture is reproduced in Fig. 9. The ring is seen to consist of a layer of smoke and a layer of transparent air, wound up in a spiral of a dozen or more complete turns.

The angular velocity of rotation appears to increase as the core of the ring is approached, the inner portions being screened from friction, if we may use the term, by the rotating layers surrounding them. This can be very nicely shown by differentiating the core, forming an air ring with a smoke core. If we make a small vortex box with a hole, say 2 cm in diameter, fill it with smoke and push very gently against the diaphragm, a fat ring emerges which rotates in a very lazy fashion, to all appearances. If, however, we clear the air of smoke, pour in a few drops of ammonia and brush a little a strong HCl around the lower part of the aperture, the smoke forms

in a thin layer around the under side of the hole. Giving the same gentle push on the diaphragm, we find that the smoke goes to the core, the rest of the ring being invisible, the visible part of the vortex spinning with a surprisingly high velocity. Considerable knack is required to form these thin cressent-like vortices, the best results being

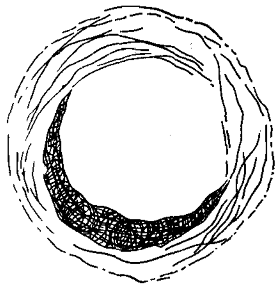


Fig. 10

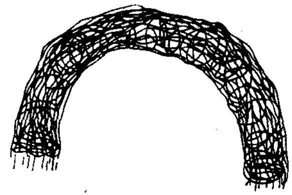


Fig. 11

usually attained after quite a number of attempts have been made. A drawing of one of these smoke-cores is shown in Fig. 10. The actual size of the vortex being indicated by dotted lines, it is instructive as showing that the air which grazes the edge of the aperture goes to the core of the ring. The experiment does not work very well on a large scale, though I have had some success by volatilising sal ammoniac around the upper edge of the aperture by means of a zig-zag iron wire heated by a current.

By taking proper precautions we can locate the smoke elsewhere, forming a perfect half-ring, as is shown in Fig. 11, illustrating in a striking manner that the existence of the ring depends in no way on the presence of the smoke. The best way to form these half-rings is to breathe smoke very gently into a paper tube allowing it to flow along the bottom, until the end is reached, when a ring is expelled by a gentle puff. A large test tube with a hole blown in the bottom is perhaps preferable, since the condition of things inside can be watched. It is easy enough to get a ring, one half of which is wholly invisible, the smoke ending abruptly at a sharply defined edge, as shown in Fig. 11, requires a good deal of practice. I have tried fully half-a-dozen different schemes for getting these half-rings on a large scale, but no one of them gave results worth mentioning. The hot wire with the sal ammoniac seemed to be the most promising method, but I was unable to get the sharp cut edge which is the most striking feature of the small rings blown from a tube.

In accounting for the formation of vortex rings, the rotary motion is often ascribed to friction between the issuing air-jet and the edge of the aperture. It is, however, friction with the exterior air that is for the most part responsible for the vortices. To illustrate this point I have devised a vortex box in which friction with the edge of the aperture is eliminated, or rather compensated, by making it equal over the entire cross-section of the issuing jet.

The bottom of a cylindrical tin box is drilled with some 200 small holes, each about 1.7 mm in diameter. If the box be filled with smoke and a sharp puff of air delivered at the open end, a beautiful vortex ring will be thrown off from the cullender surface (Fig. 12). We may even

cover the end of a paper tube with a piece of linen cloth, tightly stretched, and blow smoke rings with it.

In experimenting with a box provided with two circular apertures I have observed the fusion of two rings moving side by side into a single large ring. If the rings have a high velocity of rotation they will bounce apart, but if they are

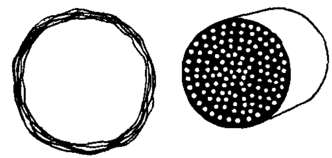


Fig. 12

sluggish they will unite. At the moment of union the form of the vortex is very unstable, being an extreme case of the vibrating elliptical ring. It at once springs from a horizontal dumb-bell into a vertical dumb-bell, so rapidly that the eye can scarcely follow the change, and then slowly oscillates into the circular form. This same phenomenon can be shown with two paper tubes held in opposite corners of the mouth and nearly parallel to each other. The air in the room must be as still as possible in either case.

On Vortex Rings

by S. Shabanov and V. Shubin

Formation of the Vortex Rings

To study vortex rings in the air under laboratory conditions, we used the apparatus designed by Professor Tait (Fig. 13). One end of this cylinder, the membrane, is covered with a flexible material such as leather. The other end, the diaphragm, has a circular opening. Two flasks, one containing hydrochloric acid (HCl), the other ammonium hydroxide (NH_4OH), are placed in the box, where they produce a thick fog (smoke) of ammonium chloride particles (NH_4Cl). By

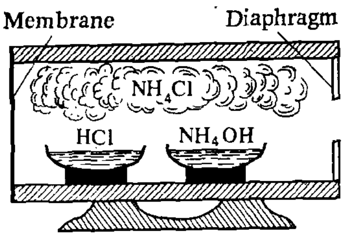


Fig. 13

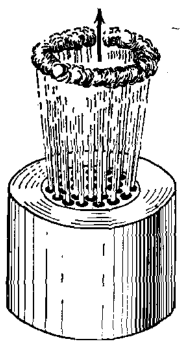


Fig. 14

tapping the membrane, we impart a certain velocity to the smoke layer close to it. As this layer moves forward, it compresses the next layer, which, in turn, compresses the layer following it, in a chain reaction that reaches the diaphragm where smoke escapes through the opening and sets formerly still air in motion. Viscous friction against the edge of the opening twists the smoky air into a vortex ring.

The edge of the opening is not the main factor in the formation of the vortex ring, however. We can prove this by fitting a sieve over the opening in the Tait's apparatus. If the edge were

important, many small vortex rings would form. Yet they do not. Even with a sieve, we still observe a single, large vortex ring (Fig. 14).

If the membrane is substituted by a plunger that is set to motion, a continuous smoke jet will appear on the edge of the opening instead of vortex rings. It is essential to provide for the

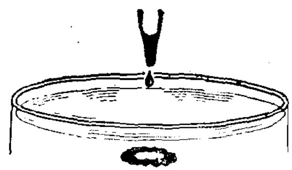


Fig. 15

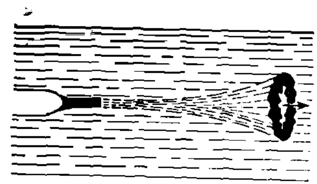


Fig. 16

intermittent outflows of smoke through the opening.

Vortex rings can be produced in water using an ordinary pipette and ink. Let a few drops of ink fall from a height of 2-3 centimetres into an aquarium with very still water, which has no convection flows. The formation of the ink rings will be very obvious in the clear water (Fig. 15).

The set up can be changed slightly: the stream of ink can be released from a pipette submerged in water (Fig. 16). The vortex rings obtained in this case are larger.

Vortex rings in water form similarly to those in the air, and the behaviour of the ink in water is similar to that of smoke in the air. In both cases viscous friction plays a vital role. Experiments show that the analogy is complete only in the first moments after the formation of the vortex, however. As it develops further, the vortex behaves differently in water and the air.

Movement of the Environment Around the Vortex Rings

What happens to the environment when a vortex forms? We can answer this question with the right experiments.

Place a lighted candle 2-3 metres away from the Tait apparatus. Now direct a smoke ring so

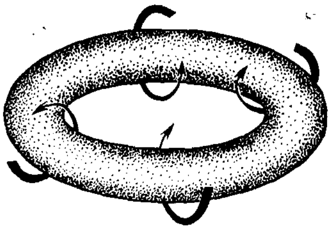


Fig. 17

that it passes the candle but misses the flam narrowly. The flame will either go out or flicke violently, proving that the movement of th vortex involves not only the visible part of th ring, but also adjacent layers of the air.

How do these layers move? Take two piece of cloth, and soak one in hydrochloric acid, an the other in ammonia solution. Hang them u about 10-15 centimetres apart. The space betwee them will immediately be filled with smok (ammonium chloride vapour). Now shoot a smok ring from the apparatus into the vapour clou As the ring passes through the cloud, the ri expands while the cloud starts moving circularl From this we can conclude that the air close t the vortex ring is circulating (Fig. 17).

A similar experiment can be set up in water. Put a drop of ink in a glass full of water that has been stirred slowly and continues to circulate. Let the water get still. You will see ink fibres in the water. Now put ink ring into the glass. When this ring passes close to the fibres, they twist.

Vortex Rings in Water

We decided to study the behaviour of vortices in water further. We know that a drop of ink

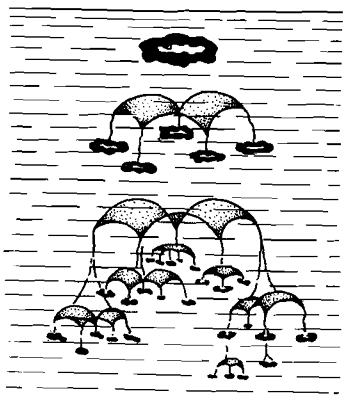


Fig. 18

placed into an aquarium from a height of 2-3 centimetres will form an ink vortex ring. This ring soon develops into several new rings, which, in turn, break into other smaller rings, and so on to form a beautiful "temple" in the aquarium (Fig. 18).

We found that the division of the initial ring into secondary rings was preceded by expansions in the large ring itself. How this can be explained? Since the environment through which the ink ring moves is nonuniform, some of its parts move faster than others, some lag behind. The ink (which is heavier than water) tends to collect in the faster sections, where it forms swelling due to surface tension. These swellings give birth to new droplets. Each droplet on the initial vortex behaves independently, eventually producing a new vortex ring in a cycle that repeats several times. Interestingly, we could not determine any regularity in this cycle: the number of rings in the "fourth generation" was different in each of ten experiments.

We also found that vortex rings require "living" space. We tested this by placing pipes of different diameters in the path of rings in water. When the diameter of the pipe was slightly larger than that of the ring, the ring disintegrated after entering the pipe, to produce a new ring with a smaller diameter. When the diameter of the pipe was four times larger than the ring diameter, the ring passed through the pipe without obstruction. In this case the vortex is not affected by external factors.

Smoke Ring Scattering

We conducted several experiments to study interaction between the smoke ring and the opening of different diameter. We also studied the relationship between the ring and a surface at various angles. (We called these experiments scattering tests.)

Consider a ring hitting a diaphragm whose aperture is smaller than the ring. Let us examine two cases. First, the ring may collide with the diaphragm when the forward motion velocity of the ring is perpendicular to the diaphragm plane and the centre of the ring passes through the centre of the diaphragm. Collision, on the other hand, may be off-centre if the centre of the ring does not align with the centre of the diaphragm. In the first case, the ring scatters when it hits

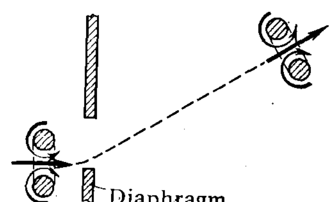


Fig. 19

the diaphragm, and a new ring with a smaller diameter forms on the other side of the diaphragm. This smaller ring forms just as it would in the Tait apparatus: the air that moves around the original ring passes through the aperture and entrains the smoke of the scattered vortex with it. A similar situation can be observed when a ring collides centrally with an aperture of equal or somewhat larger diameter. The effect of an off-centre collision is even more interesting: the newly formed vortex emerges at an angle to the original direction of the motion (Fig. 19). Try to explain why.

Now let us consider an interaction of the ring with a surface. Experiments show that if the surface is perpendicular to the velocity of the ring, the ring spreads without losing its shape. This can be explained as follows. When the air stream inside the ring hits the surface, it produces a zone of elevated pressure, which forces the ring to expand *uniformly*. If the surface is at a slant relative to the original direction, the vortex recoils when colliding with it (Fig. 20). This phenomenon can be explained as the effect

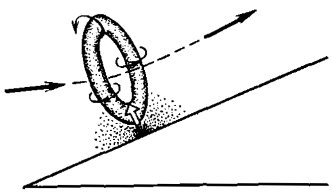


Fig. 20

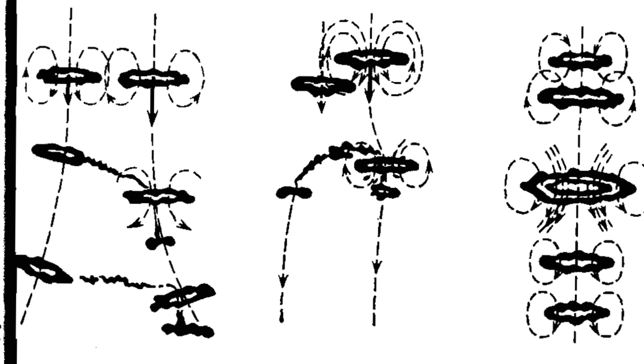
of elevated pressure in the space between the ring and the surface.

Interaction of Rings

The experiments with interacting rings were undoubtedly the most interesting. We conducted these experiments with rings in water and in the air.

If we place a drop of ink into water from a height of 1-2 cm and, a second later, let another drop fall from 2-3 cm, two vortices moving at different velocities will form. The second drop will move faster than the first (v_2 greater than v_1). When the rings reach the same depth, they begin to interact with each other in one of three possible ways. The second ring may overtake the first

one without touching it (Fig. 21*a*). In this situation the water currents generated by the rings repel one another. Some of the ink from the first ring flows over to the second ring because the more intensive currents in the second ring pull the ink with them. Occasionally, some of this



(a) (b) (c)

Fig. 21

ink passes through the second ring and forms a new, smaller ring. The rings then begin to break down, and the process continues as we observed earlier.

The second ring may, on the other hand, touch the first while overtaking it (Fig. 21*b*). As a result, the more intensive flows of the second ring destroy the first one. Normally, new smaller vortices emerge from the remaining ink cluster of the first ring.

Finally, the rings may collide centrally (Fig. 21*c*), in which case the second ring passes through the first and shrinks, whereas the first ring expands. As before, this is a result of the interaction of the water currents of both rings. The rings begin to break down at a later stage.

The interaction of smoke rings in the air was investigated using a Tait apparatus with two apertures. The results of the experiments greatly depended on the force and duration of the impact on the membrane. In our setup the membrane was struck with a heavy pendulum. If the distance l between the apertures is less than the diameter d

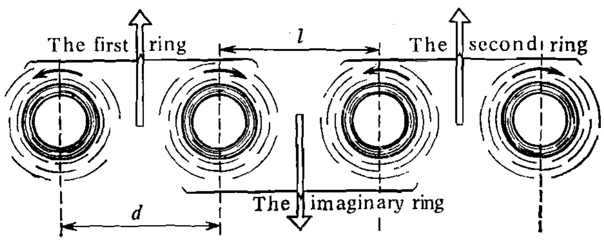


Fig. 22

of each aperture (l is less than d) the two ai currents mix and produce a single vortex ring If $d < l < 1.5d$, no ring appears at all. In al other cases two rings appear. If l is more than $4d$ the rings do not interact. If $1.5d < l < 4d$, th rings converge at first, although they occasionall separate again before disintegrating. The forma tion of an "imaginary" ring in the space betwee the rings explains this convergence (Fig. 22) The imaginary ring moves in the opposite direc tion from the planes of the real rings, which begin to turn toward one another and graduall move closer.

We were not able to determine why the ring eventually disintegrate completely.

Tornado Models

by V. Mayer

The tornado is one of the most awesome and mysterious phenomena in nature. Its power is so great that almost nothing can withstand its force. How are tornadoes able to carry heavy objects over such considerable distances? How do they form? Modern science has yet to answer these and many other questions completely.

Is it possible to simulate a tornado in the laboratory? With the following two experimental setups, you can make a water model of a tornado even at home.

1. Solder a brass-or tin-plate disc about 40 mm in diameter and 0.5-1 mm thick to the shaft of a micromotor like those commonly used in toy machines. The disc must be exactly perpendicular to the shaft to ensure that the disc will run true. Use grease or mineral oil to seal the bearings of the shaft. The contact studs and the soldered wires leading to them should be protected with a plasticine layer.

Attach a plasticine cake about 5 mm thick to the bottom of a glass (or jar) about 9 cm in diameter and 18 cm high. Attach the micromotor to it, allowing a clearance between the lower end of its shaft and the plasticine cake. The wires from the micromotor should be fastened to the inside wall of the glass with adhesive or plasticine. Fig. 23 shows the setup ready for operation.

Fill the glass with water. Then pour in a layer of sunflower oil 1-2 cm thick. When the wires from the micromotor are connected to a flashlight battery, the disc begins rotating and causes the liquid in the glass to circulate. This circulation disturbs the surface between the water and oil, and a cone filled with the oil soon forms. The cone grows until it touches the disc, which then breaks the oil into drops, turning the liquid turbid. After the micromotor is shut off, the oil

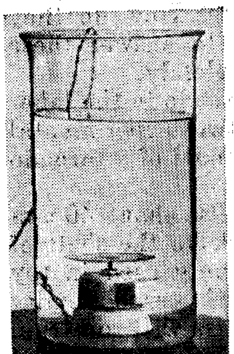


Fig. 23

drops return to the surface where they reform a continuous layer. The experiment can then be repeated.

Figures 24*a* and 24*b* show photographs of the formation of the air cone. We modified the experiment slightly here by filling the glass with water only.

2. An even more convincing model of a tornado can be constructed by soldering a piece of copper wire (or a knitting needle) about 25 cm in length and 2 mm in diameter to the shaft of a micromotor. Solder a rectangular brass or tin plate about 0.5 × 10 × 25 mm in size at right

angles to the wire (Fig. 25*a*). Switch on the motor to check the operation of this stirrer. If necessary, straighten its extended shaft (the wire) to minimize wobbling.

Lower the stirrer vertically into a glass of water 15-20 cm in diameter and 25-30 cm high. Switch on the motor. A cone will grow gradually

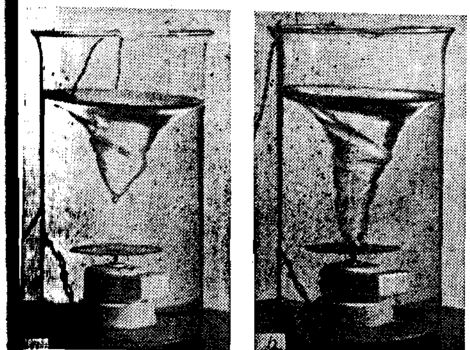


Fig. 24

on the water surface to form a tornado that extends to the rotating plate (Fig. 25*b*, *c*, *d*). As the tornado touches the plate, many air bubbles appear, signifying a vortex around the plate. If you hold the motor in your hand, the tornado will behave very much like a living creature. You can spend hours watching its "predatory" surges.

Continue the experiment by placing a wooden block on the water surface. The block will be sucked in by the tornado. Try to adjust the rotation speed of the stirrer so that the block remains underwater at the same depth for a long time.

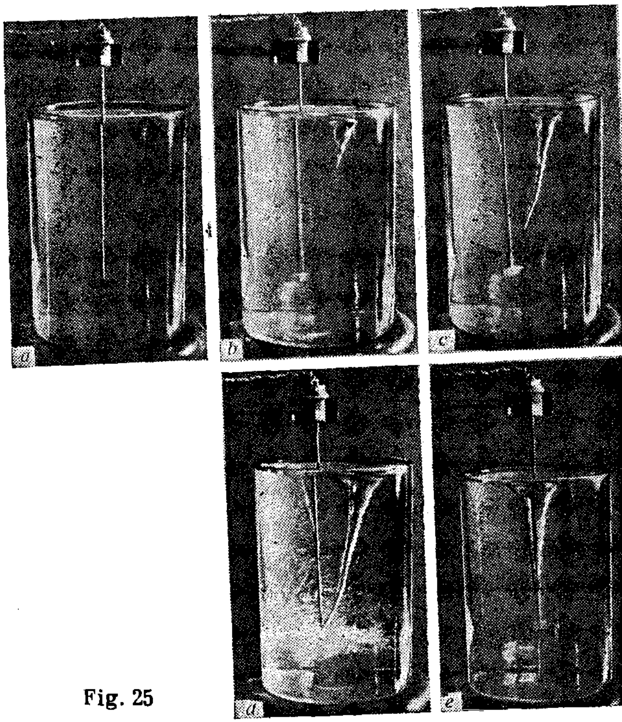


Fig. 25

The tornado will suck in bodies lying on th
bottom of the glass before the stirrer is switche
on if their density is greater than that of wat
(which is not true of the wooden block).

Align the shaft of the motor with the axis
the glass. You will see a cone moving down th
shaft and air bubbles which mark its continu
tion under the plate (Fig. 25*e*). If you place som
well washed river sand on the bottom of th

glass, you will be able to observe the structure of the tornado under the plate.

These experiments show that tornadoes are always caused by a vortex in a liquid or gas.

The Aerodynamics of Boomerangs *

by Felix Hess

Imagine throwing a piece of wood into the air, making it fly around in a large circle and having it come to rest gently at your feet. Preposterous! Yet of course this is exactly what a boomerang does, provided that it has the right shape and is thrown properly.

As is well known, boomerangs originated among the aboriginal inhabitants of Australia. Although boomerang-like objects have been found in other parts of the world as well (in Egypt and India, for instance), these objects are not able to return, as far as I know. The reader may be a little disappointed to learn that most Australian boomerangs also do not return. Australian boomerangs can be roughly divided into two types: war boomerangs and return boomerangs. Those of the first type are, as their name implies, made as weapons for fighting and hunting. A good war boomerang can fly much farther than an ordinary thrown stick, but it does not return. Return boomerangs, which exist in much smaller numbers, are used almost exclusively for play.

Actually things are not quite as simple as this. There are many kinds of aboriginal weapons

* An abridged version of an article that first appeared in the November issue of *Scientific American* for 1968.

in Australia, a number of which look like boomer-angs, so that the distinction between boomerangs and throwing or striking clubs is not a sharp one. Neither is the distinction between war boomer-angs and return boomerangs. The shape of boom-erangs can differ from tribe to tribe (Fig. 26).

Whether a given boomerang belongs to the return type or not cannot always be inferred easily from its appearance. Return boomerangs however, are usually less massive and have a less obtuse angle between their two arms. A typical return boomerang may be between 25 and 75 cen-timeters long, 3 to 5 centimeters wide an 0.5 to 1.3 cm thick. The angle between the arm may vary from 80 to 140 degrees. The weigh may be as much as 300 grams.

The characteristic banana-like shape of mos boomerangs has hardly anything to do with thei ability to return. Boomerangs shaped like th letters *X*, *V*, *S*, *T*, *R*, *H*, *Y* (and probabl other letters of the alphabet) can be made t return quite well. The essential thing is the cros section of the arms, which should be more conve on one side than on the other, like the win profile of an airplane (see Fig. 27). It is only fo reasons of stability that the overall shape of boomerang must lie more or less in a plane. Thu if you make a boomerang out of one piece o natural wood, a smoothly curved shape followin the grain of the wood is perhaps the most obviou choice. If you use other materials, such a plywood, plastics or metals, there are conside rably more possibilities.

How does one throw a return boomerang? A a rule it is taken with the right hand by one o

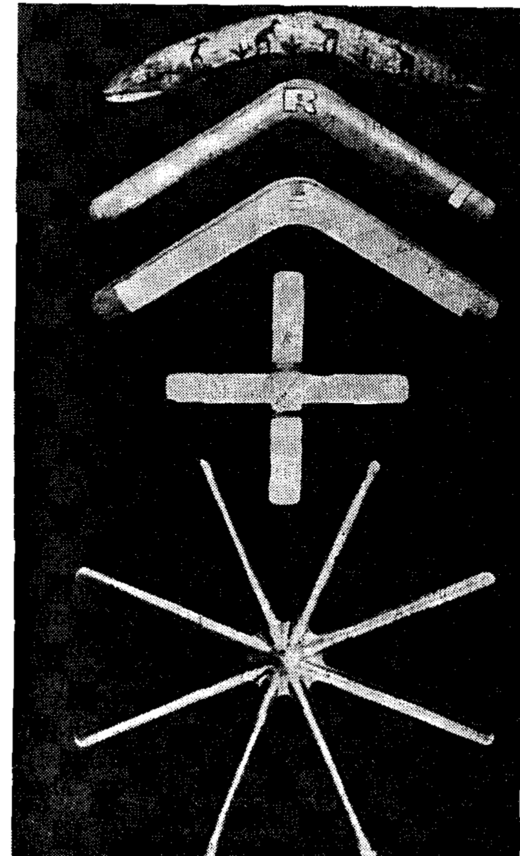


Fig. 26

its extremities and held vertically upward, the more convex, or upper, side to the left. There are two possibilities: either the free extremity points forward—as is the practice among the Australians—or it points backward. The choice depends entirely on one's personal preference. Next, the

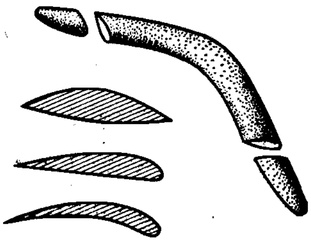


Fig. 27

right arm is brought behind the shoulder and the boomerang is thrown forward in a horizontal or slightly upward direction. For successful throwing, two things are important. First, the plane of the boomerang at the moment of its release should be nearly vertical or somewhat inclined to the right, but certainly not horizontal. Second, the boomerang should be given a rapid rotation. This is accomplished by stopping the throwing motion of the right arm abruptly just before the release. Because of its inertia the boomerang will rotate momentarily around a point situated in the thrower's right hand. Hence it will acquire a forward velocity and a rotational velocity at the same time.

At first the boomerang just seems to fly away, but soon its path curves to the left and often upward. Then it may describe a wide, more or less circular loop and come down somewhere near

the thrower's feet, or describe a second loop before dropping to the ground. Sometimes the second loop curves to the right, so that the path as a whole has the shape of a figure eight (Fig. 28). It is a splendid sight if the boomerang, quite near again after describing a loop, loses speed,

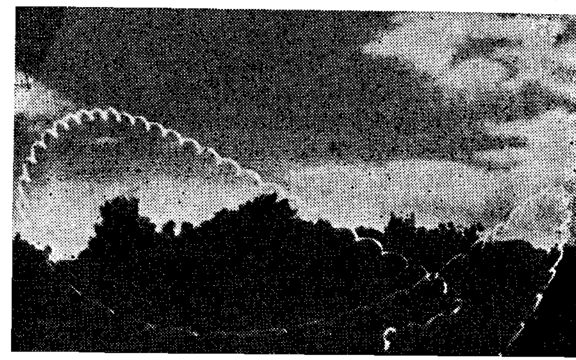


Fig. 28

hovers some 3 meters above your head for a while and then slowly descends like a helicopter.

Every boomerang has its own characteristics with respect to ease of throwing, shape of path and hovering ability. Moreover, one boomerang can often describe very different orbits depending on the way it is thrown. The precision of return depends to a large extent on the skill of the thrower, who must take into account such factors as the influence of wind. The greatest distance during a flight may be 40 meters, but it can also be much less or perhaps twice as much; the highest point can be as high as 15 meters above the ground or as low as 1.5 meters. I have heard that with modern boomerangs of Australian make distances of more than 100 meters can be attained, still followed by a perfect return, but I regret to say that so far I have not been able to make a boomerang go beyond about 50 meters.

In the foregoing general description it was tacitly assumed that the thrower was right-handed and used a "right-handed" boomerang. If one were to look at an ordinary right-handed boomerang from its convex side while it was in flight, its direction of rotation would be counter-clockwise. Hence one can speak of the leading edge and the trailing edge of each boomerang arm. Both the leading and the trailing edges of an aboriginal boomerang are more or less sharp. The leading edge of a modern boomerang arm is blunt, like the leading edge of an airplane wing. Sometimes the arms have a slight twist, so that their leading edges are raised at the ends.

The entire phenomenon must of course be explained in terms of the interaction of the boomerang with the air; in a vacuum even a boomerang would describe nothing but a parabola. This interaction, however, is difficult to calculate exactly because of the complicated nature of the problem. Let us nonetheless look at the matter in a simple way.

If one throws a boomerang in a horizontal direction, with its plane of rotation vertical, each boomerang arm will "wing" the air. Because of the special profile of the arms the air will exert a force on them directed from the flatter, or lower, side to the more convex, or upper, side

(Fig. 29). This force is the same as the lifting force exerted on the wings of an airplane. In a right-handed throw the force will be directed from the right to the left as viewed by the thrower.

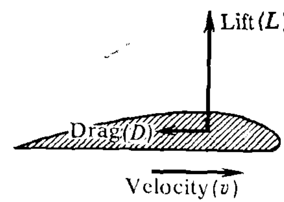


Fig. 29

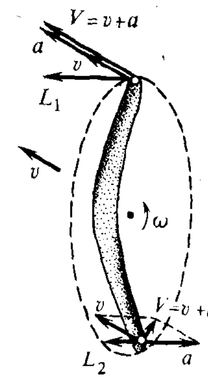


Fig. 30

This force alone, however, is not sufficient to make a boomerang curve to the left.

Following one boomerang arm during its motion, one can see that its velocity with respect to the air is not constant. When the arm points upward, the forward velocity of the boomerang adds to the velocity due to the rotation; when it points downward, the two velocities are in opposite directions, so that the resultant speed will be smaller or even vanish at some points (see Fig. 30). Thus on the average the boomerang experiences not only a force from the right to the left but also a torque acting around a horizontal axis, which tends to cant the boomerang with its upper part to the left. Actually this turning over will not be observed because the boomerang is spinning rapidly and hence behaves like a gyroscope.

Now, a gyroscope (which really is nothing more than a rapidly spinning flywheel) has the property that, when a torque is exerted on it, it does not give way to that torque but changes its orientation around an axis that is perpendicular to both the axis of rotation and the axis of the exerted torque; in the case of a boomerang the orientation turns to the left. This motion is called precession. Thus the boomerang changes its orientation to the left, so that its plane would make a gradually increasing angle to its path were it not for the rapidly increasing forces that try to direct the path parallel to the boomerang plane again. The result is that the path curves to the left, the angle between boomerang plane and path being kept very small.

In actual practice one often sees that, although the plane of the boomerang is nearly vertical at the start of the flight, it is approximately horizontal at the end. In other words, the plane of the boomerang slowly turns over with its upper part to the right; the boomerang in effect "lies down". Let us now consider the question in more detail.

Because much is known about the aerodynamic forces on airfoils (airplane wings), it is convenient to regard each boomerang arm as an airfoil. Looking at one such wing, we see that it moves forward and at the same time rotates around the boomerang's center of mass. We explicitly assume that there is no motion perpendicular to the plane of the boomerang. With a cross

boomerang (as with the rotor of a helicopter) the center of mass lies at the intersection of the wings, but this is not the case with an ordinary boomerang. Here one arm precedes the center of mass, whereas the other arm follows it. We call both arms "eccentric", the eccentricity being the distance from the arm to the center of mass. A preceding arm has a positive eccentricity, a following arm a negative eccentricity. A fixed point of a wing feels an airstream that changes continuously in magnitude and direction with respect to that part of the wing. Sometimes the airstream may even blow against the trailing edge of the wing profile, which can easily be imagined if one thinks of a slowly rotating boomerang with high forward velocity and looks at the arm pointing downward. What are the forces on an airfoil moving in this special manner?

Let us first look at a simpler case: an airfoil moving in a straight line with a constant velocity v with respect to the air (Fig. 31). It is customary to resolve the aerodynamic force into two components: the lift L (perpendicular to v) and the drag D (opposite to v). These are both proportional to v^2. If the spanwise direction of the wing is not perpendicular to the velocity, v has a component parallel to the wing that has no influence; therefore we replace v by its component perpendicular to the wing, or the "effective velocity" V_{eff}. In this case the forces are proportional to $(V_{eff})^2$.

Looking at the boomerang arm again, it is clear that each point on the arm takes part in the boomerang's forward velocity v. The velocity with respect to the air due to the rotation, however, is different for each point. For a rotational velocity ω and a point at a distance r from the axis of rotation (which passes through the boomerang's center of mass), this velocity is ωr. For each point on the arm one can reduce the velocities v and ωr to one resultant velocity. Its component perpendicular to the arm is V_{eff}

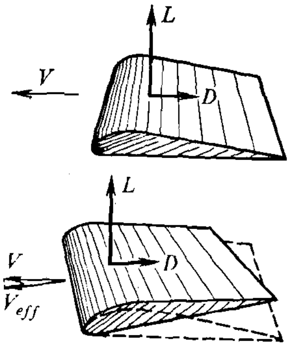


Fig. 31

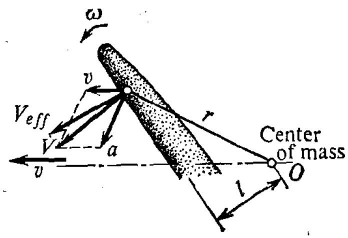


Fig. 32

(Fig. 32). Of course, the value of V_{eff} for a particular point on the arm will change continuously during one period of revolution. One assumes that the contributions to the lift and drag of each part of a boomerang arm at each moment are again proportional to $(V_{eff})^2$.

Calculations were made of the following forces and torques, averaged over one period of revolution: the average lift force L; the average torque T, with its components T_1 around an axis parallel to v (which makes the boomerang turn to the

left) and T_2 around an axis perpendicular to v (which makes the boomerang "lie down") (Fig. 33); the average drag D, which slows down the forward velocity v, and the average drag torque T_D, which slows down the rotational velocity ω. It turns out that none of these quantities except T_2 depends on the eccentricity for boomerang

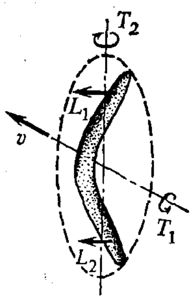


Fig. 33

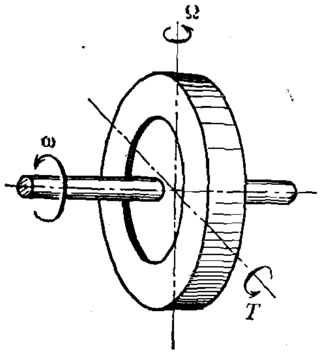


Fig. 34

arms that are otherwise identical; T_2 is exactly proportional to the eccentricity.

The forces and torques acting on a boomerang as a whole are obtained by adding their values for each of its arms. The contributions to T_2 by arms with opposite eccentricity may partly or completely cancel each other.

Now we come to the important question: How does a boomerang move under the influence of these aerodynamic forces and torques (and of the force of gravity, of course)? As mentioned earlier, the average torque T causes the gyroscopic precession of a boomerang. Let us take a closer look at the gyroscope. If a gyroscope spins around its axis with a rotational velocity ω and one exerts a torque T on it, acting around an axis perpendicular to the spin axis, the gyroscope precesses around an axis perpendicular to both the spin axis and the torque axis (Fig. 34). The angular velocity of the precession is called Ω. A very simple connection exists between Ω, ω, T and the gyroscope's moment of inertia I, namely $\Omega = T/I \cdot \omega$. We have seen that for a boomerang T is proportional to ωv, so that the velocity of precession Ω must be proportional to $\omega v/I\omega$, or v/I. Hence the velocity of precession does not depend on ω, the rotational velocity of the boomerang.

An even more striking conclusion can be drawn. The velocity of precession is proportional to v/I, the factor of proportionality depending on the exact shape of the boomerang. Therefore one can write $\Omega = cv$, with c a characteristic parameter for a certain boomerang. Now let the boomerang have a velocity twice as fast; it then changes the orientation of its plane twice as fast. That implies, however, that the boomerang flies through the same curve!

Thus, roughly speaking, the diameter of a boomerang's orbit depends neither on the rotational velocity of the boomerang nor on its forward velocity. This means that a boomerang has its path diameter more or less built in.

The dimensions of a boomerang's flight path are proportional to the moment of inertia of the boomerang, and they are smaller if the profile of the arms gives more lift. Therefore if one wants a boomerang to describe a small orbit (for instance in a room), it should be made out of light material. For very large orbits a heavy boomerang is needed with a profile giving not much lift (and of course as little drag as possible).

Now one has everything needed to form the equations of motion for a theoretical boomerang. These equations can be solved numerically on a computer, giving velocity, orientation and position of the boomerang at each instant.

How do these calculated paths compare with real boomerang flights? For an objective comparison it would be necessary to record the position of a boomerang during its flight. This could be done by means of two cameras. In order to control the initial conditions, a boomerang-throwing machine would be necessary. As yet I have had no opportunity to do such experiments, but I did manage to record one projection of experimental boomerang paths with a single camera. In the wing tip of a boomerang a tiny electric lamp was mounted, fed by two small 1.5-volt cells connected in series, placed in a hollow in the central part of the boomerang (see Fig. 35). In this way the boomerang was made to carry during its flight a light source strong enough to be photographed at night. Some of the paths recorded in this manner are shown in Fig. 36; calculated orbits are added for comparison in Fig. 37.

Because the camera was not very far from the thrower, those parts of the trajectories where the boomerang was close to the camera appear exaggerated in the photographs. This effect of perspec-

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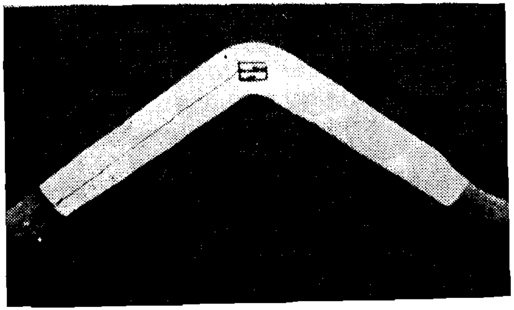

Fig. 35

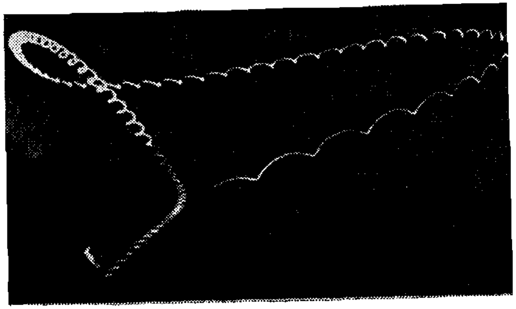

Fig. 36

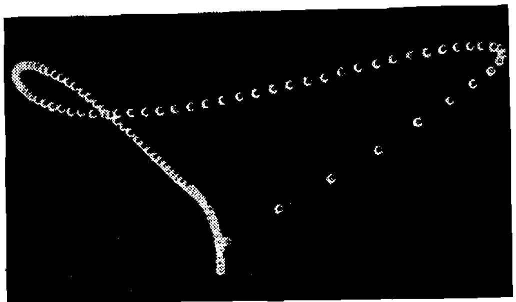

Fig. 37

tive was taken into account in the accompanying calculated paths. The reader may decide for himself whether or not he finds the agreement between theory and experiment satisfactory. At any rate, the general appearance and peculiarities of real boomerang paths are reproduced reasonably well by this theory.

A Hydrodynamic Mechanism in a Falling Test Tube

by G. I. Pokrovsky

Fill a standard test tube with water, and, holding it a few centimeters above the table top,

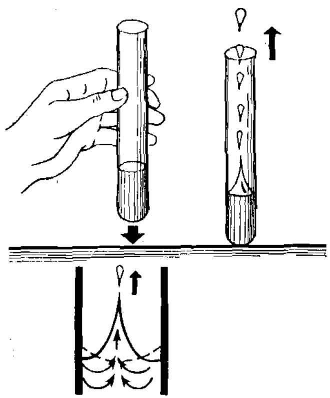

Fig. 38

let it drop vertically (see Fig. 38). The surface of the table should be sufficiently hard to produce an elastic impact. During impact, the meniscus of the water in the test tube, which is normally concave because of capillary force, will rapidly level out, and a thin stream of water will suddenly burst upward from the centre. Figure 38 shows the water surface before impact (broken line) and after impact (solid line). The stream upward separates into drops, and the uppermost drop reaches a height substantially higher than that from which the tube is dropped. This indicates that the energy in the water is redistributed during impact so that a small fraction of water close to the centre of the meniscus shoots out of the tube at high velocity.

A device that redistributes energy is called a mechanism. Usually, this word is applied to solid parts (levers, toothed wheels, etc.), although there are liquid and even gaseous mechanisms. The water in the tube is just one example of such a mechanism.

Hydrodynamic mechanisms are especially important when very great forces that cannot be withstood by conventional solid parts are involved. The force of explosive material in a cartridge, for example, can be partially concentrated by making a concave cavity in the cartridge, which is lined with a metal sheet. The force of the explosion compresses the metal and produces a thin metallic jet whose velocity (if the shape of the lining is correct) may reach the escape velocity of a rocket.

Thus, this modest experiment on a very simple phenomenon in a test tube relates to one of the most interesting problems of the hydrodynamics of ultra high speeds.

An Instructive Experiment with a Cumulative Jet

by V. Mayer

In Professor G.I. Pokrovsky's simple and elegant experiment on the hydrodynamics in a test tube, a tube partially filled with water is dropped from a few centimetres above a hard surface, thus producing a jet of water from the tube upon impact. Since the water at the edges clings slightly to the glass of the tube, the meniscus is concave. Upon impact the tube and the water in it stop sharply, which causes the water to accelerate rapidly. The water behaves as if it were very heavy and its surface levels out. The water around the edges resides, and a thin jet of water gushes out from the center of the tube for a short time.

You can set up a similar, perhaps even more striking experiment. Carefully cut off the bottom of a test tube to make a glass pipe 15 mm in diameter and about 100 mm long. Seal the fluted end of the pipe with a piece of rubber cut from a toy balloon. Fill the pipe with water and, covering the open end with your finger, lower that end into a glass of water. Remove your finger and adjust the pipe so that about a centimetre of water is left inside the pipe. The water inside the pipe should be level with the water surface in the glass. Fix the pipe vertically to a support. Now slightly tap the piece of rubber stretched over the pipe. A cumulative jet of water will immediately rise inside the pipe and reach the piece of rubber itself.

Figures 39 and 40 show drawings of photographs taken at different moments during this experiment. They depict different stages of the formation and disintegration of various cumulative jets. The top two pictures show the jet proper; the bottom two depict the break-up of the jet into individual drops.

Try to explain the results of this experiment by comparing it with the one described by Pokrovsky. This setup is especially interesting because it allows us to observe the actual formation of a cumulative jet, which is more difficult in the experiment with a falling test tube because the human eye is not fast enough to register the phenomena that take place during impact. Nevertheless, we advise you to return to the experiment with the falling tube once more to examine the details of the formation of the jet. With this in mind we suggest you solve the following problems.

EXERCISES

1. Determine whether the shape of the test tube bottom affects stream formation. Does the stream develop because the bottom directs the shock wave in the water? To answer this question, solder a tin bottom of any shape (plane or concave, for example) to a thin-wall copper pipe. Use these modified test tubes in the experiments described above to prove that the shape of the bottom does not influence the formation of the stream. Thus, the results of this experiment cannot be explained as the direction of the wave by the bottom.
2. Determine whether it is necessary for the liquid to wet the walls of the test tube. Place a small piece of paraffin inside a glass test tube, and melt the paraffin over the flame of a dry fuel. Rotate the tube over the flame to coat the inside with a thin paraffin film. Now,

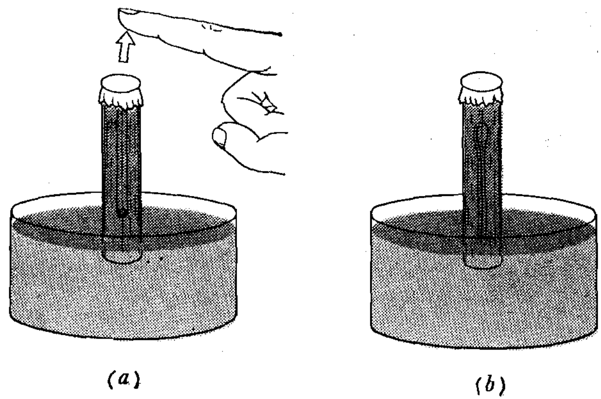

Fig. 39

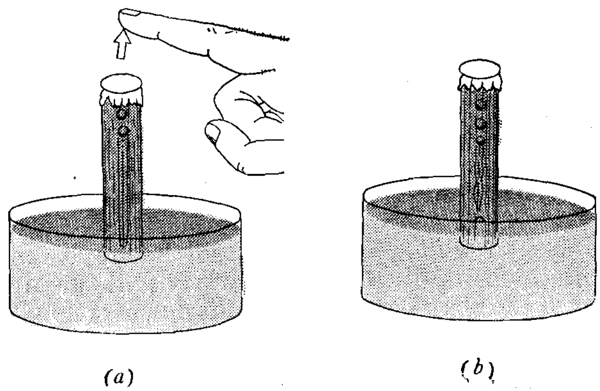

Fig. 40

repeat the Pokrovsky experiment with this coated test tube. The cumulative jet should not form, which means that the walls of the tube must be wet for the experiment to work properly.
3. What other experiments can be set up to obtain a cumulative jet in a tube that is stationary relative to the observer?

Magic with Physics

by V. Mayer and E. Mamaeva

Take a glass pipe, one end of which is tapered like that of a pipette, and show the pipe to your audience. Hold a glass of water (heated to 80-90 °C) by its rim in your other hand, and show it to your audience, too. Now, lower the tapered end of the pipe into the glass, and let the pipe fill with water. Close the upper end of the pipe with your finger and remove the pipe from the glass (Fig. 41).

Your audience will be able to see air bubbles appear at the lower end of the pipe. They grow, leave the walls of the pipe, and rise to the top of the pipe. But the water stays in the pipe! Now, empty the pipe back into the glass by removing your finger from the upper end, and wave the pipe in the air several times before taking some more water. Close the upper end with your finger again, and quickly pull the pipe out of the glass and turn it upside down (Fig. 42). A strong stream of water over a metre high will burst out of the pipe.

Although the secret of this trick is very simple indeed, your audience is unlikely to guess it,

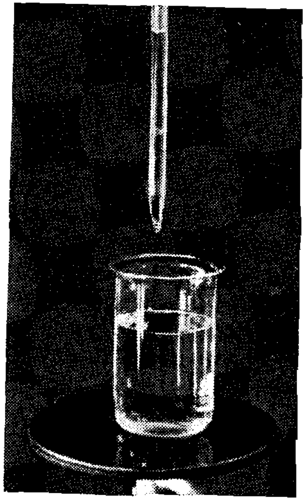

Fig. 41

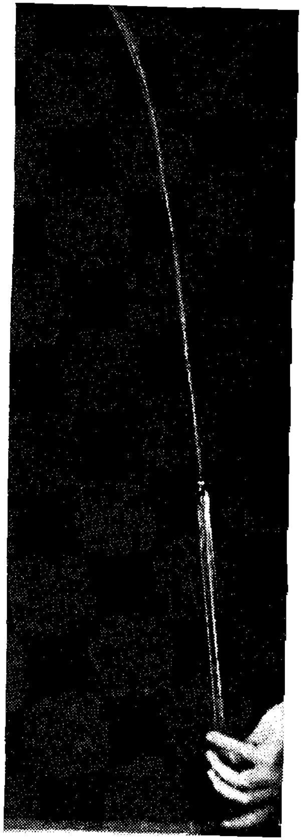

Fig. 42

The glass contains water heated to 80-90 °C whereas the pipe is room temperature (about 20 °C). You should be able to explain why no water leaves the pipe at first without any hints, The explanation for the powerful stream of water is more complicated. When hot water enters the pipe from the glass, the air in the upper part of the pipe remains at room temperature because the pipe conducts heat poorly. After you have closed the upper opening and turned the pipe upside down, the hot water streams downward, heating the air quickly. The pressure rises, and the expanding air shoots the remaining water out through the tapered end of the pipe.

Use a glass pipe 8-12 mm in diameter and 30-40 cm long for this experiment. The smaller opening should be about 1 mm in diameter. Between tricks the pipe should be well cooled (you can even blow through it) because the height of the fountain will depend on the temperature difference between the air and the water in the pipe. The optimal amount of water in the pipe fluctuates from 1/4 to 1/3 of its volume and can easily be determined empirically.

A Drop on a Hot Surface

by M. Golubev and A. Kagalenko

Turning an iron upside down and levelling it horizontally, let a little water drop on its hot surface. If the temperature of the iron is slightly over 100 °C, the drop will diffuse as expected and evaporate within a few seconds. If, however, the iron is much hotter (300-350 °C), something unusual will happen: the drop will bounce between 1 and 5 millimetres off the iron (as a ball bounces off the floor) and will then move over

the hot surface without touching it. The stability of such a state depends, first of all, on the temperature of the surface: the hotter the iron, the calmer the drop. Moreover, the "longevity" of the drop, the time before it evaporates completely, increases many times over. The rate of evaporation depends on the size of the drop. Larger drops shrink quickly to 3-5 mm, whereas smaller drops last longer, without noticeable changes. In one of our experiments a drop 3 mm in diameter remained for about 5 minutes (300 seconds) before evaporating completely.

What is the explanation for this strange phenomenon? When the drop first touches the heated surface, its temperature is about 20 °C. Within fractions of a second, its lower layer are heated to 100 °C, and their evaporation begins at so fast a rate that the pressure of the vapour becomes greater than the weight of the drop. The drop recoils and drops to the surface again. A few bounces are enough to heat the drop through to boiling temperature. If the iron is well heated, the drop calms down and moves over the iron at a distance slightly above the iron. Obviously, the vapour pressure balances the weight of the drop in this condition. Once such a steady state is reached, the drop is fairly stable and can "live" a long time.

When the drop is small, its shape is roughly that of a sphere. Larger drops are vertically compressed. On a hot surface the drop seems to be supported by a vapour cushion. The reaction force that develops as a result causes the deformation of the drop. The larger the drop, the more noticeable the deformation.

Oscillations, for example, compression, tension, or even more complex oscillation, may develop, especially in large drops (Figs. 43 and

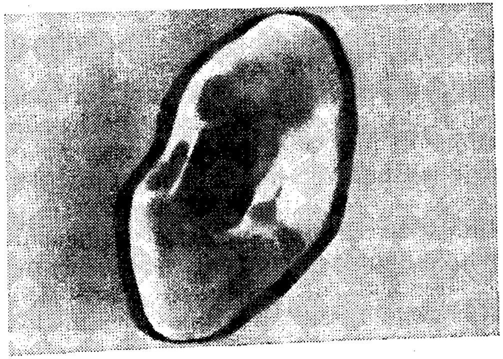

Fig. 43

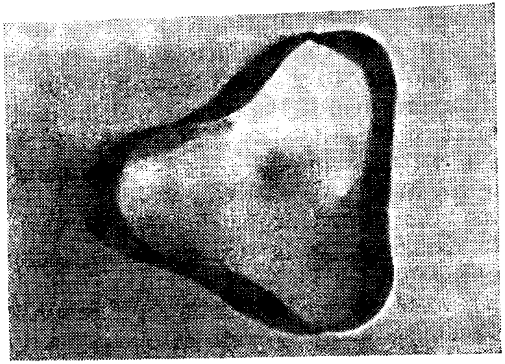

Fig. 44

44). The photograph in Fig. 43 shows a dark spot in the centre of the drop. This is vapour bubble. In large drops several such bubbles may

appear. Occasionally, a drop assumes the shape of a ring with a single, big vapour bubble in the middle. When this occurs the evaporation proceeds so intensively that the drop shrinks visibly. Figure 44 shows one of the most interesting kinds of oscillations: a "trigonal" drop.

Keep the following advice in mind when conducting experiments like those described above.

1. The iron should be as smooth as possible, without scratches or irregularities. When a drop runs into such an irregularity, its life is considerably reduced. Why?

2. The iron should be fastened to a support horizontally. In our experiments we used a tripod for geodetical instruments.

3. Safety precautions should not be neglected. The conductors of the iron should be reliably insulated, take care not to scald your hands with boiling water.

Surface Tension Draws a Hyperbola

by I. Vorobiev

The coefficient of the surface tension of a liquid can be determined by measuring the rise of wetting liquid in a capillary tube. Capillary tubes and a microscope for measuring their inner diameters are not always readily available, however. Fortunately, the tubes can be easily replaced with two glass plates. Lower the plates into a glass of water, and draw them together gradually. The water between them will rise: it is sucked in by the force of surface tension (Fig. 45).

The coefficient of surface tension σ can easily be calculated from the rise of the water y and the clearance between the plates d. The force of the surface tension is $F = 2\sigma L$, where L is the length of the plate (multiplied by 2 because the water contacts both plates). This force retains a layer of water that weighs $m = \rho L\, dy$,

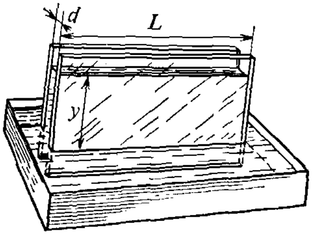

Fig. 45

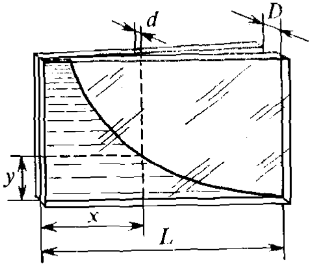

Fig. 46

where ρ is the water density. Consequently,

$2\sigma L = \rho L dy g$

Hence, the coefficient of the surface tension is

$$\sigma = 1/2 \rho g d y \quad (1)$$

A more interesting effect can be obtained by pressing the plates together on one side and leaving a small clearance on the other (Fig. 46). In this case the water will rise, and the surface between the plates will be very regular and smooth (provided the glass is clean and dry).

It is easy to infer that the vertical cross section of the surface is a hyperbola. And we can prove this by replacing d with a new expression for the clearance in formula (1). Then $d = D\frac{x}{L}$ follows from the similarity of the triangles (see Fig. 46).

Here D is the clearance at the edge of the plates; L is the length of the plate, and x is the distance from the line of contact to the point where the clearance and the rise of the water are measured. Thus,

$$\sigma = 1/2 \rho g y D \frac{x}{L},$$

or

$$y = \frac{2\sigma L}{\rho g D} \cdot \frac{1}{x} \quad (2)$$

Equation (2) is really the equation of the hyperbola.

The plates for this experiment should be about 10 cm by 20 cm size. The clearance on the open side should be roughly the thickness of a match stick. Use a deep tub like those photographers use in developing pictures to hold the water. For ease in reading the results, attach a piece of graph paper to one of the plates. Once we have a graph drawn by the water, we can check whether the curve is actually a hyperbola. All the rectangulars under the curve should have the same area (Fig. 47).

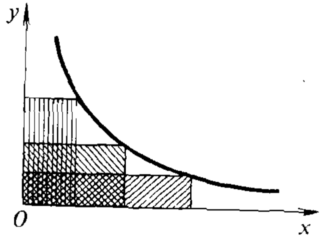

Fig. 47

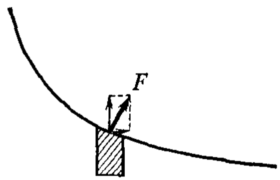

Fig. 48

If you have a thermometer, you can study the dependence of surface tension of water temperature. You can also study the influence of additives on water tension.

The force of surface tension F is directed at right angles to the line of contact between the water and the glass (Fig. 48). The vertical component of the force is balanced by the weight of the water column. Try to explain what balances its horizontal component.

Experiments with a Spoonful of Broth

by V. Mayer

The next time you are served bouillon for dinner, scoop up a big spoonful, don't swallow it immediately. Look carefully at the broth instead:

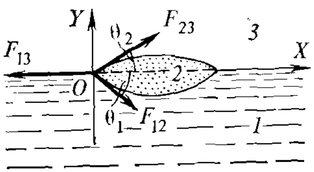

Fig. 49

you will see large drops of fat in it. Note the size of these droplets. Now pour some of the broth back into your soup bowl, and look again at the broth in the spoon. The drop of fat should have diffused and gotten thinner but bigger in diameter. What is the reason behind this phenomenon?

First let us see under what conditions a drop of fat can lie on the surface of the broth without diffusing. Look at Fig. 49. A drop of liquid *2*

(the fat) lies on the surface of liquid *1* (the broth). The drop is shaped roughly like a lens. The environment *3* above the bowl is a mixture of the vapours of liquids *1* and *2*. Media *1*, *2*, and *3* meet at the circumference of the drop. Isolate an increment of this circumference (close to point O in Fig. 49) of Δl length. Three forces of surface tension act upon this increment. At the interface of liquids *1* and *2*, force $\boldsymbol{F}_{12}$ acts, tangential to the interface and equal in module to

$$|\boldsymbol{F}_{12}| = \sigma_{12}\Delta l,$$

where σ_{12} is the surface tension at the interface of media *1* and *2*. Similar forces $\boldsymbol{F}_{13}$ and $\boldsymbol{F}_{23}$ act at the interfaces of *1* and *3*:

$$|\boldsymbol{F}_{13}| = \sigma_{13}\Delta l$$

and *2* and *3*:

$$|\boldsymbol{F}_{23}| = \sigma_{23}\Delta l.$$

Here σ_{13} and σ_{23} are the appropriate surface tensions.

Obviously, the drop reaches equilibrium if the total of all these forces equals zero

$$\boldsymbol{F}_{12} + \boldsymbol{F}_{13} + \boldsymbol{F}_{23} = 0$$

or their projections on coordinates X and Y (after the substitution of appropriate absolute values and the cancellation of Δl) are

$$\sigma_{13} = \sigma_{12}\cos\theta_1 + \sigma_{23}\cos\theta_2, \qquad (1)$$

$$\sigma_{12}\sin\theta_1 = \sigma_{23}\sin\theta_2$$

Here, θ_1 and θ_2 are the angles between the tangents to the surface of medium *2* and the surface of medium *1*. These angles are called *angles of contact*.

It follows from Eq. (1) that equilibrium of the drop is possible if the surface tensions are related as

$$\sigma_{13} < \sigma_{12} + \sigma_{23}.$$

Since surface phenomena in a liquid are practically independent of the gaseous environment over it, we assume that

$$\sigma_{13} = \sigma_1 \quad \text{and} \quad \sigma_{23} = \sigma_2.$$

We call σ_1 and σ_2 surface tensions of liquids *1* and *2*, respectively. In this case these values refer to the surface tensions of both the broth and the fat.

So, a drop of fat will float on the surface of the broth without diffusing if the surface tension of the broth is less than the total of the surface tensions of the fat and the interface between the broth and the fat:

$$\sigma_1 < \sigma_2 + \sigma_{12} \qquad (2)$$

If the drop is very thin (almost flat), θ_1 and θ_2 will be small ($\theta_1 = \theta_2 = 0$) and the equilibrium condition for the drop will be

$$\sigma_1 = \sigma_2 + \sigma_{12}$$

When $\sigma_1 > \sigma_2 + \sigma_{12}$ there are no angles θ_1 and θ_2 for which Eq. (1) would hold true. Therefore, liquid *2* does not make a drop on the surface of liquid *1* in this case, but diffuses on its surface in a thin layer.

Now let us try to explain the results of our experiment with a spoonful of broth. Drops of fat

float on the broth, which means that Eq. (2) holds. Why do they diffuse on the surface of the broth if the amount of broth is reduced? What has changed? Since the surface tensions of the fat σ_2 and of the broth-fat interface σ_{12} remain unchanged, we have to assume that by pouring out some of the broth, we change the surface tension of the broth σ_1. But the broth is water (to a first approximation). Can the surface tension of water be changed by simply decreasing the amount? Obviously not. The broth, however, is not plain water but rather water covered with a thin layer of fat. By pouring out some of the broth, we reduce the amount of fat, and its layer on the broth surface becomes thinner. This apparently reduces the surface tension of the broth and as a result, the fat drops diffuse.

To test this hypothesis, try the following experiment. Pour some tap water into a clean saucer which has no traces of fat. Put a tiny drop of sunflower oil on its surface (a pipette or a clean refill from a ball-point pen can be used for the purpose). The first drop should diffuse completely over the surface, while the next drops do not diffuse but form a lens. Carefully pour out some of the water, and the drops will diffuse again.

Now return to the experiment with the spoonful of broth. If you watch the behaviour of the fat closely, you will notice that the drops rupture and reunite. Figures 50-55 show photograph of one such experiment. We filled a clean glass dish with tap water coloured with Indian ink that contains no alcohol. We placed eight very small drops of sunflower oil on the surface with a thin glass tube (see Fig. 50). When we sucked a small

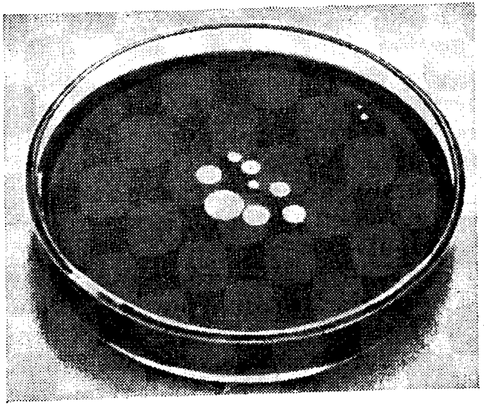

Fig. 50

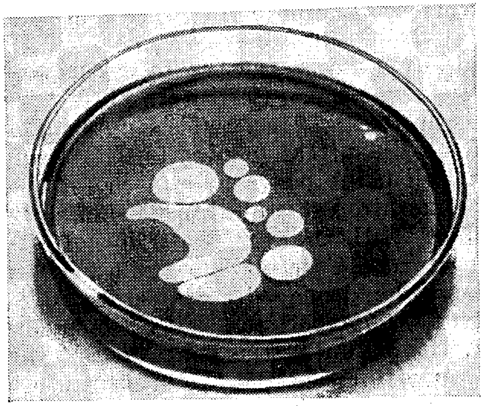

Fig. 51

amount of water out with a rubber bulb, the drops enlarged. When more water was removed, the drops became even larger and changed shape (because of the water currents). The beginnings

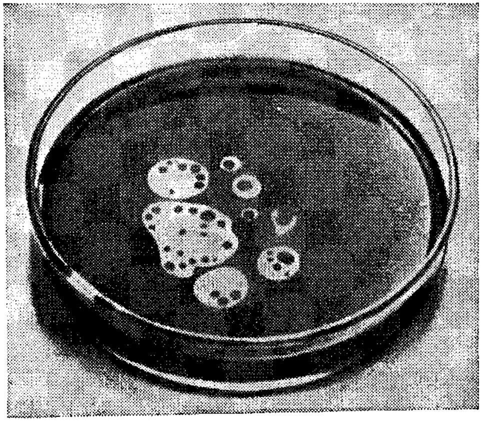

Fig. 52

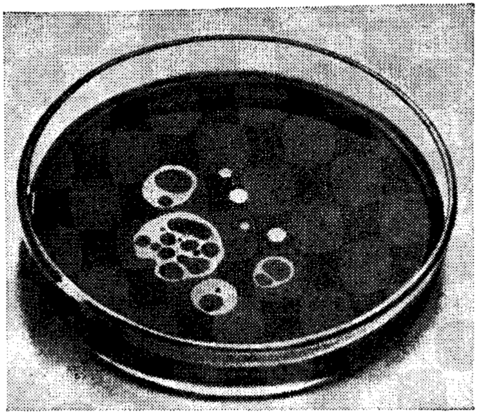

Fig. 53

of future ruptures also appeared (see Fig. 51). Further modifications occued rrspontaneously. The ruptures grew and united into a single large rupture. The drop became a ring, which finally

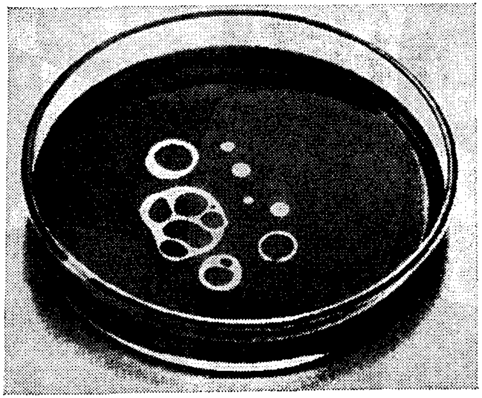

Fig. 54

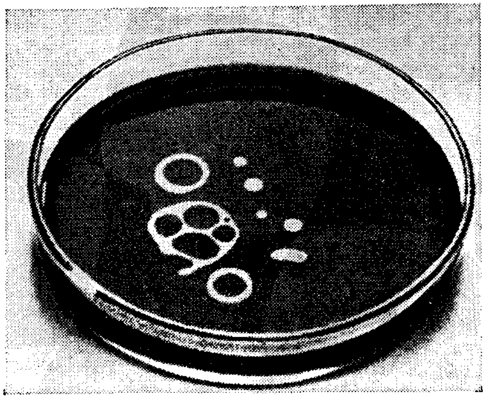

Fig. 55

broke and rearranged into a new drop (Figs. 52-55).

Perhaps now you will agree that it is worthwhile watching your soup before putting it into your mouth!

How to Grow a Crystal

by M. Kliya

Modern industry cannot do without a wide variety of crystals. Crystals are used in watches, transistorized radioes, computors, lasers, and many other machines. Even nature's enormous laboratory is no longer able to meet the demands of developing technology, and special factories have appeared where various crystals, ranging in size from very small crystals to large crystals weighing several kilos, are grown.

The methods for growing crystals vary and often require high temperatures and tremendous pressure (for example, when growing artificial diamonds). But some crystals can be grown even in your home laboratory. The simplest crystals to grow at home are potash alum crystals, $KAl(SO_4)_2 \cdot 12H_2O$. This absolutely harmless substance is widely available (alums are occasionally used to purify tap water). Before growing our own crystals, however, let us take a closer look at the process itself.

When a substance is dissolved in water at a constant temperature, dissolution stops after a certain time, and such a solution is said to be saturated. Solubility refers to the maximal quantity of the substance that dissolves at a given temperature in 100 grams of water. Normally, solubility rises with a rise in temperature. A solution that is saturated at one temperature becomes unsaturated at a higher temperature.

If a saturated solution is cooled, the excess of the substance will precipitate. Figure 56 shows the dependence of potash alum solubility on temperature. According to the graph, if 100 grams of a solution saturated at 30 °C are cooled to 10 °C, over 10 grams of the substance should precipi-

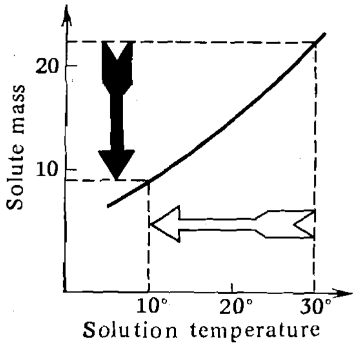

Fig. 56

tate. Consequently, crystals can be grown by cooling a saturated solution.

Crystals can also be grown by evaporation. When a saturated solution evaporates, its volume decreases, while the amount of dissolved substance remains unchanged. The excess of substance thus produced falls as a precipitate. To see how this occurs, heat a saturated solution, and then cover the jar containing the unsaturated solution with a glass plate and allow it to cool to a temperature below the saturation temperature. The substance may not precipitate with this method, in which case we will be left with a supersaturated solution. This is because we need a seed, a tiny crystal or even a speck of the same sub-

stance, to form a crystal. Usually, multiple small crystals can be generated simply by shaking the jar or removing the cover. To grow large crystals, the number of seed crystals should be limited. As an artificial seed, a crystal grown earlier works best of all.

The seed crystal can be grown as follows. Take two clean glass jars. Pour warm water into one of them, and then add alum. Stir the mixture, and watch the dissolution process closely. When dissolution stops, carefully drain the solution into another jar, taking care not to pour any of the undissolved substance into the second jar. Cover the jar with a glass plate. When the solution has become cool, remove the plate. After a short time, you should see many crystals in the jar. Let them take their time to grow, before selecting the largest as a seed crystal.

Now we are ready to grow our own crystal. First of all, we need proper glassware. To remove undesirable nuclei from the walls of the vessels, sterilize them over the spout of a boiling teapot. Then make another warm saturated solution in one jar, and drain it into another. Heat this warm saturated solution of alum a little more. Then cover the jar with a plate, and set it aside to cool. As the temperature of the solution approaches the saturation temperature, lower the seed crystal you made earlier into the jar. Since the solution is still unsaturated, the seed crystal will begin to dissolve. But as soon as the temperature drops to the saturation point, the seed crystal stops dissolving and starts growing. (If your seed crystal dissolves completely, introduce another crystal.) The crystal will continue to grow once the solution has cooled, if you lift the cover and let the water evaporate. Do not let dust enter the jar. Growth will continue for two or three days.

When growing crystals try not to move or touch the jar. After a crystal has developed, re-

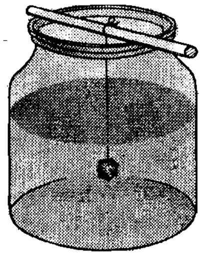

Fig. 57

move it from the solution, and dry it carefully with a paper napkin so it will retain its shine.

The crystals develop differently, depending on whether the seed crystal is placed on the bottom of the jar or suspended from a thread (Fig. 57). You can even grow 'a necklace' by running a thread several times over the seed crystal before suspending it in the solution.

Growing crystals is an art, and you may not be completely successful right away. Do not get disappointed. With a little persistence and care, you can produce beautiful crystals.

Crystals Made of Spheres

by G. Kosourov

Before we can predict, explain, or understand the properties of a crystal, we must determine its

structure. If we know the arrangement and the symmetry of atoms in the crystal lattice, we can tell whether the crystal is piezoelectric, i.e., whether a certain voltage is generated at its edges under mechanical compression, whether the crystal is capable of ferroelectric transition, which develops at a specific temperature and is characterized by the formation of an intrinsic electric field, whether the crystal generates a light wave of double frequency when transmitting a laser beam, and so on. The structure of the crystal carries abundant information about the crystal itself.

Different atomic arrangements in crystals can be studied with a few simple props. We can build models of crystals, following the principles used in nature with ordinary ball bearings. Even crystallographers use these three-dimensional models, which clearly show the specifics of atomic arrangements in complex structures. Before starting our experiments, we should make a few theoretical observations.

Crystal lattices result from the interaction of atomic forces. When the atoms are close together, repulsive forces prevail and increase sharply with attempts to bring the atoms together. Attractive forces prevail at greater distances and decrease rather gradually with distance. When atoms are drawn together by attractive force, the potential energy of their interaction decreases, just as the potential energy of a falling stone decreases. This potential energy is minimal at the point at which attractive and repulsive forces are equal, and it increases sharply as the atoms draw closer. The dependence of potential energy on distance is shown in Fig. 58. In equilibrium, atoms assume places of minimal potential energy. If there are many atoms, this tendency leads to the repeated formation of the most energy-efficient configuration of a small group of atoms. This configuration is called the unit cell.

Some substances have very complex structures. The unit cell of some silicates, for example,

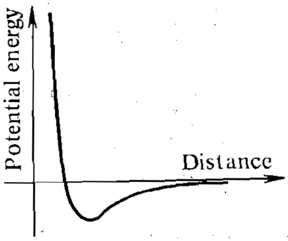

Fig. 58

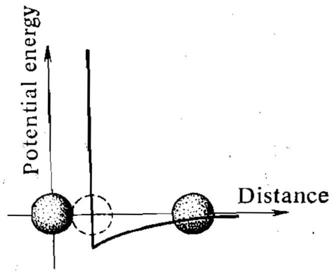

Fig. 59

contains over 200 atoms. Other substances, many metals, for example, form their crystal lattice by a very simple algorithm. Naturally, we shall start from the simplest coordinations. In our experiments atoms are represented by metal spheres. Elastic forces, developing as a result of the conjugation of the spheres, serve as the repulsive force, and the attractive force is provided by gravity.

Stretch a thin piece of rubber (this may be a piece of a surgical glove) over the opening of a jar, box, or section of pipe, and fasten it with a rubber band. Place two spheres on the piece of

rubber. The rubber will sag slightly, and the spheres will be attracted to one another. Their potential energy, which depends on distance, is shown approximately in Fig. 59 and is very similar to the dependence in Fig. 58. If we put about 30 spheres on the piece of rubber and shake them slightly, they will arrange themselves in regular rows (Fig. 60). The centres of the spheres will lie

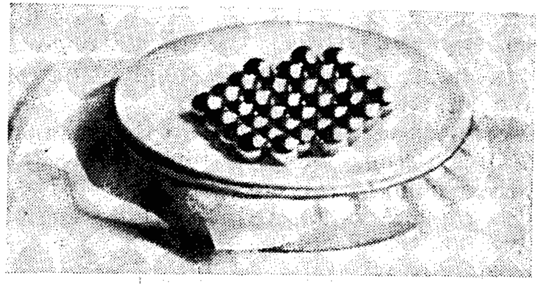

Fig. 60

at the apexes of equilateral triangles, every side of which equals the diameter of the sphere. The spheres will fill the whole plane forming a lattice called a hexagonal (Gr. *hex* six and *gonia* a corner, angle). Each sphere is surrounded by six spheres touching each other. Their centres form regular hexagons.

If you turn the lattice one-sixth of a revolution around an axis through the centre of any one of the spheres, some of the spheres will change places, but the overal arrangement of the system in space will remain the same. The lattice of spheres will translate itself into the original position. After six such rotations each sphere resumes its original position. In such cases crystallographers say that the axis of symmetry of the sixth order, which is oriented perpendicular to the plane of the lattice, passes through the centre of each sphere. This axis makes the lattice "hexagonal". In addition to the symmetry axes of the sixth order, third-order symmetry axes pass through the centres of the holes formed by neighbouring spheres. (The third-order symmetry axis is a straight line; each time the lattice is rotated 120 degrees around this axis, the original configuration repeats. Irregularly shaped bodies have first-order symmetry axes since they return to the original position after a single complete revolution. Conversely, the symmetry axis of infinite order passes through the plane of a circle at right angles since the circle translates itself into the original position at an infinitely small angle of rotation.)

The following discussions will be clear only if you have spheres for building models of different crystals. Consider the holes on either side of a row of spheres (Fig. 61). Since the number of holes in either row equals the number of spheres in a row, an infinite lattice of spheres has twice as many holes as spheres. The holes form two hexagonal lattices, similar to those formed by the centres of the spheres. These three lattices are shifted relative to one another in such a way that the sixth-order symmetry axes of each lattice coincide with the third-order symmetry axes of the other two lattices.

The second layer of spheres fills one of the lat-

tices of holes to form a hexagonal lattice of contiguous spheres, similar to the first such lattice. The elasticity of the piece of rubber, however, may not provide enough attractive force to hold the spheres of the second and third layers. Therefore, since we know how the spheres in the bottom layer lie, let us make an equilateral triangle from plywood (Fig. 62), the sides of which equal an integer number of spheres (seven in our model), and fill it with spheres of the bottom layer.

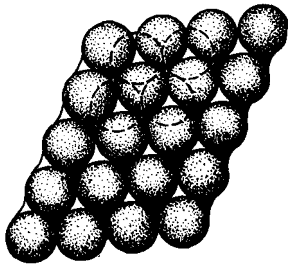

Fig. 61

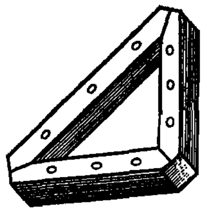

Fig. 62

The second layer of spheres can fill any lattice of holes, but when we reach the third layer, we find the holes are not equivalent. The centres of one of the lattices are arranged over the centres of the spheres in the bottom layer, whereas the second lattice lies over the vacant holes of the bottom layer. We shall begin by putting spheres into the holes above the spheres of the bottom layer. In this case the third layer will be an exact replica of the bottom arrangement of spheres; the fourth layer will repeat the second layer, and so on. Each layer will repeat itself every second layer. Our pyramid will be rather fragile (Fig. 63) because the "attractive" force in our model acts downwards only, and the spheres in the holes along the edges are easily pressed out by the spheres of the layers above.

This kind of packing, called hexagonal closest packing, is typical of beryllium, magnesium, cadmium, and helium crystals at low temperatures and pressures over twenty five atmospheres. This packing has only one system of closely packed, parallel layers. The third-order symmetry axis, which passes through the centre of each sphere, is perpendicular to this system of layers. The symmetry order is thus reduced: when the axis passes through centres of the even-layered spheres, the lattice has the sixth-order symmetry; the same axis passes through the centres of the holes in the odd layers, and the symmetry of the odd layers, relative to this axis, is, therefore, only of the third order. Nevertheless, this packing is called hexagonal, because it can be viewed as two hexagonal lattices of even and odd layers. Note also that the empty holes in all layers are arranged one over the other and channels pass through the whole hexagonal structure, into which rods, whose diameter is 0.155 that of the diameter of the sphere can be inserted. The centre lines of these channels are the third-order symmetry axes. Figure 63 shows the model of a hexagonal structure with rods placed in the channels.

Now let us put the spheres from the third layer into the holes above the vacant holes of the bottom layer. We can construct two different pyramids (Figs. 64 and 65), depending on the system

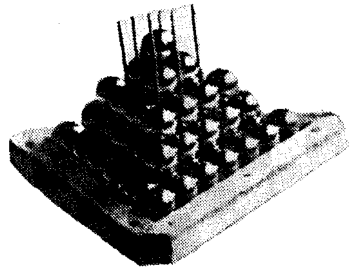

Fig. 63

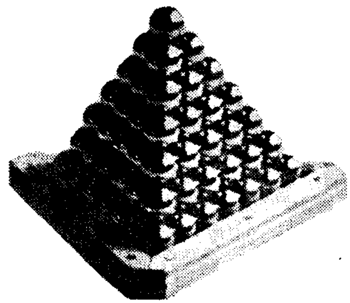

Fig. 64

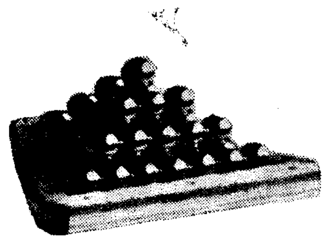

Fig. 65

of holes we select for the second layer of spheres. The faces of the first pyramid are equilateral triangles with hexagonal packing, which do not differ from the packing of the bottom layer of the pyramid. In other words, our pyramid is a tetrahedron, one of the five possible regular polyhedrons. This packing has four families of closely packed layers, whose normals coincide with the third-order symmetry axes of the tetrahedron which pass through its apexes. In such a packing the layers repeat every third layer. The lateral faces of the second pyramid are isosceles triangles, and the pyramid itself is part of a cube, intercepted by the plane formed by the diagonals of the faces with a common apex (Fig. 66). The packing in the lateral faces of such a pyramid forms a square lattice with its rows parallel to the diagonals of the cube face.

Obviously, we have only one type of packing with two different orientations. If we remove the spheres from the edges of the tetrahedron, the faces of the cube will emerge. Conversely, by removing the spheres that make up the edges of the cube, we turn the cube into a tetrahedron. This packing, called cubic closest packing, is characteristic of neon, argon, copper, gold, platinum and lead crystals. Cubic closest packing possesses all the elements of cubic symmetry. In particular, the third-order symmetry axes of the tetrahedron coincide with the space cube diagonals, which are also third-order symmetry axes for the cube. This packing is based on a cube of fourteen spheres. Eight of the spheres form the cube, and six form the centres of its faces. If you look closely at the second pyramid

(Fig. 66), you will find this elementary cube at the apex. Cubic closest packing can be viewed as a combination of four simple cubic lattices. The equality of all the spheres of the packing is especially noticeable from this angle. Since the hexagonal and cubic closest packings can be produced by superimposing hexagonal layers onto one another, the two obviously have the same density, or space factor, despite the difference in symmetry.

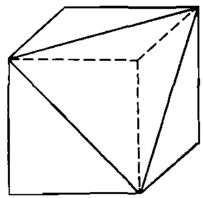

Fig. 66

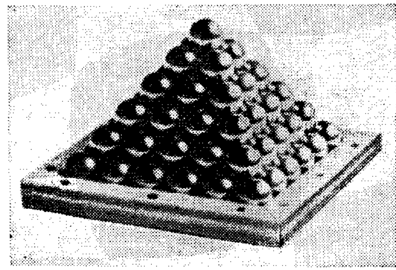

Fig. 67

If we build a square form and place spheres in a square lattice, we shall get another close packing. Although the spheres in each layer are not packed in the closest possible way, the holes between them are deeper, and, therefore, the layers lie closer than in a hexagonal structure. If we complete the packing, we will get a tetrahedral pyramid (Fig. 67) whose side faces are equilateral triangles in which the spheres are packed hexagonally. If we add another such pyramid with its apex downward, we shall get a third polyhedron (after the tetrahedron and the cube): an octahedron with eight faces. Obviously, this is also the cubic closest packing with the faces of the cube parallel to the plane of the base. Remove the spheres forming the edges, and you will find five spheres in the upper intercept plane which form the face of an elementary cube.

These models can be used in a number of physical experiments. By shaking the piece of rubber,

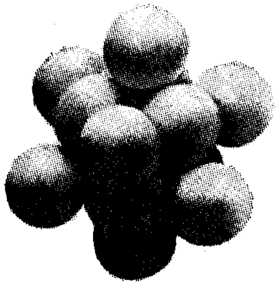

Fig. 68

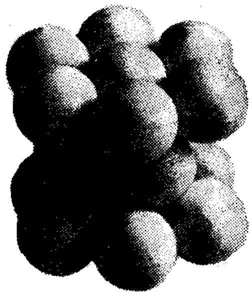

Fig. 69

for example, you can simulate the heat-induced motion of atoms. (You will see how 'a rise in temperature' destroys the packing of the spheres.)

Since each hexagonal layer occupies relatively shallow holes of the next layer, the layers are loosely bound, and slippage develops easily. If you slide one hexagonal layer against another, you will see that easy slippage, in which the layers move as a whole, occurs in three directions. A similar situation can be observed in real crystals, which explains the specifics of plastic deformation in crystals.

Models can be built from any kind of sphere. If you do not have ball bearings, use large necklace beads or even small apples. Figures 68 and 69 show unit cells of cubic and hexagonal

packings made of ping-pong balls glued together. Ping-pong balls, which are readily available and make workable models, are highly recommended, especially for junior-high and high-school physics classes.

Various packings of contiguous balls are important in crystallography, and we shall discuss them again. Meanwhile, get some balls and build models!

A Bubble Model of Crystal

by Ya. Geguzin

On Simulation

In the difficult process of interpreting experimental facts or theoretical propositions, almost everyone needs an image, a visible presentation, a simplified model of the subject. Perhaps one of the most important skills a scholar or teacher needs is the ability to construct images, analogies, and models, which can illustrate certain physical phenomenon and, thus, enlarge our understanding of them. What should such a model be? What must it be able to show? What can one expect from the model and what are its constraints? First, we expect our model to be a learning aid. It must contain no false data but must include at least a fraction of the truth pertinent to the subject. In everyday life, of course, we scorn halftruth. But 'halftruth' is a term of high approbation in relation to models. Finally, the model should be clear and easily comprehensible without dull commentary.

The very best model needs no explanation at all since its clarity gives it the force of a proof.

There are many convincing and elegant models in physics, particularly in solid state physics. In this article we shall discuss a 'live' model, which illustrates and reflects the structure flaws, and complicated interactions of real crystal very well. This is not a new model. It was conceived by the outstanding British physicist L. Bragg in the early 1940s and realized by Bragg and his colleagues V. Lomer and D. Naem. Therefore, we shall call it the BLN model after Bragg, Lomer, and Naem.

What Do We Want to Simulate?

The answer is clear: real crystal. Real crystal is a vast set of identical atoms or molecules arranged in strict order to form a crystal lattice. Occasionally, this order is disturbed, signifying the presence of defects in the crystal. Another very important characteristic of crystals is the interaction of the atoms forming the crystal. We will discuss this interaction a bit later. Now we will simply state that they do interact! Without interaction, the atoms would form a heap of disorderly arranged atoms rather than a crystal. The maintenance of order in crystals is a direct consequence of this interaction.

Another widely used model is the so-called dead model of crystal, in which wooden or clay balls are bound by straight wires. The balls represent atoms, and the wires are the symbols of their bonds in 'frozen' state. The model is 'dead' since it 'freezes' the interaction of the atoms. In

this reasonable and very useful model, different kinds of atoms are represented by balls of different colour and size, and wires of different length represent the distance between the atoms. Although the model does not reflect all the truth about the crystal, it does convey the truth without false assertions. The model, of course, cannot depict the motion of the atoms, but it reflects the order of their position very clearly. The dead model is an outstanding aid in depicting the space arrangement of atoms or in identifying the most likely directions of deformation or electric current in a crystal. The model is indispensable in representing the possible arrangement of atoms in unidentified or little studied crystals on the basis of experimental data and so-called general considerations. This technique of modeling with balls and wires aided in one of the most important discoveries of the twentieth century, the identification of the structure of the DNA molecule, which certainly speaks well for the usefulness of the dead model!

Our objective, however, is to simulate a 'live' rather than a 'dead' crystal. Obviously, to do so, we need to simulate the interaction of atoms in crystal, to revitalize the interaction that is frozen in the wires and balls.

The Interaction of Atoms in Crystal

Perhaps the most important characteristic of such interaction stems directly from the simple fact that the distance between two neighbouring atoms in real crystal has a definite value at a constant temperature. (We are speaking, of course, about the distance between the positions around which atoms fluctuate in heat induced motion. The amplitude of these fluctuations is considerably smaller than the distance between atoms.) The distance has a definite value since if we try to stretch it, the atoms resist the effort and attract one another, and if we try to reduce the distance, the atoms repel each other. The fact that this distance is determinate allows us to conclude that atomic interaction is characterized by attraction and repulsion simultaneously. At a certain distance between atoms (we call it determinate), the forces of attraction and repulsion become equivalent in absolute values. The atoms in the lattice are located at exactly this distance.

It would be useful to be able to simulate the competition of attractive and repulsive forces. Such a technique would revitalize atomic interaction in crystal. The authors of the BLN model created just such a method. Instead of wooden and clay balls, they used tiny soap bubbles.

The Interaction of Soap Bubbles on Water Surface

Two soap bubbles on the surface of a body of water are not indifferent to each other: they are first attracted to one another but, after touching, are repelled. This phenomenon can be observed in a very simple experiment, for which we will need a shallow bowl, a needle from a syringe, the inner balloon from a volley ball, and an adjustable clamp to control the compression of the nozzle of the balloon. Fill the bowl with

soapy water almost to the top, and add a few drops of glycerol to stabilize the bubbles that we will blow onto the surface of the water. Inflate the balloon. Then clamp the nozzle, and insert the needle into it (the butt end first, of course). Immerse the other end of the needle into the water (not deeply) and release the clamping pressure slightly (Fig. 70). The air that escapes the needle at regular intervals will develop into identical

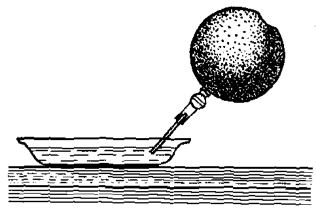

Fig. 70

soap bubbles. We shall need many such bubbles in future experiments, but for this first experiment, try to make only two bubbles, some distance from one another. If you are not successful immediately, try again. You should succeed by the fourth or fifth time, at least. Bubbles 1-2 mm in diameter work the best.

Once the bubbles are made, you can watch their movements. The bubbles will move (without our interference) towards one another, slowly at first and then more rapidly. When they collide, they do not touch at a single point but make dents on the surface. The interaction of a pair of identical bubbles will vary from that of a pair of bubbles of different size. Watch!

Now let us consider the origin of the force that drives the bubbles together spontaneously. Think of two matchsticks lying on the surface of the water. Since the bubbles and the matchsticks are both soaked by the water, the nature of their interaction is generally the same. Two bubbles floating close together form a very complex surface with the water, however, whereas that of the two matchsticks is much simpler and, thus, easier to study (Fig. 71). The force that brings the

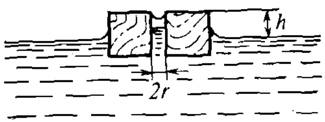

Fig. 71

two floating matchsticks together develops as follows. Water soaks the matchsticks, and the surface of the water near the sticks is, therefore, curved. This curvature generates force that acts upon the liquid. The force is determined by surface tension and directed, in this case, upward (we shall assume the matchsticks are completely soaked). Under the effect of this force, the liquid rises along the sides of the matchsticks, the rise being more pronounced in the region between the sticks (Fig. 71). The liquid appears to stretch, and the pressure in the liquid drops relative to the atmospheric pressure, by an additional pressure $\Delta p = \frac{2\sigma}{d} = \frac{\sigma}{r}$, where σ is the coefficient of surface tension, d is the distance between the matchsticks, and $r = d/2$ is the curvature radius of the surface of the liquid. Consequently, the absolute value of the pressure of the liquid on the matchsticks in the area between them is less than

the atmospheric pressure that acts upon the sticks from the outside. Thus, the absolute value of the force that draws the sticks together is

$$|F| = \Delta p\, S = \frac{2\sigma}{d}\, hl = \frac{4\sigma^2 l}{\rho\, |g|\, d^2} \sim \frac{1}{d^2}$$

From this we can predict an interesting phenomenon. Since $F \sim 1/d^2$, in a viscous environment the matchsticks should draw together with a ve-

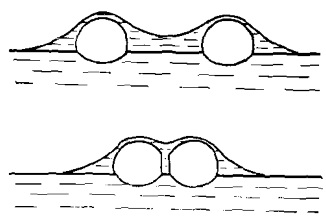

Fig. 72

locity that increases as the distance between them decreases. The bubbles also accelerate as they draw closer (Fig. 72). We filmed the movement of the bubbles in our laboratory by placing a movie camera over the bowl containing the soap solution. As soon as the bubbles started moving, we switched the camera on (Fig. 73). We were able to watch the bubbles drawing together right up to their collision. Once they have collided, a repulsive force starts acting. The force is caused by an increase of gas pressure in the mutually compressed bubbles (Fig. 74), which pushes the bubbles apart.

Soap bubbles are apparently suitable crystal models, if we create a number of identical bubbles on the surface of the soap solution rather than

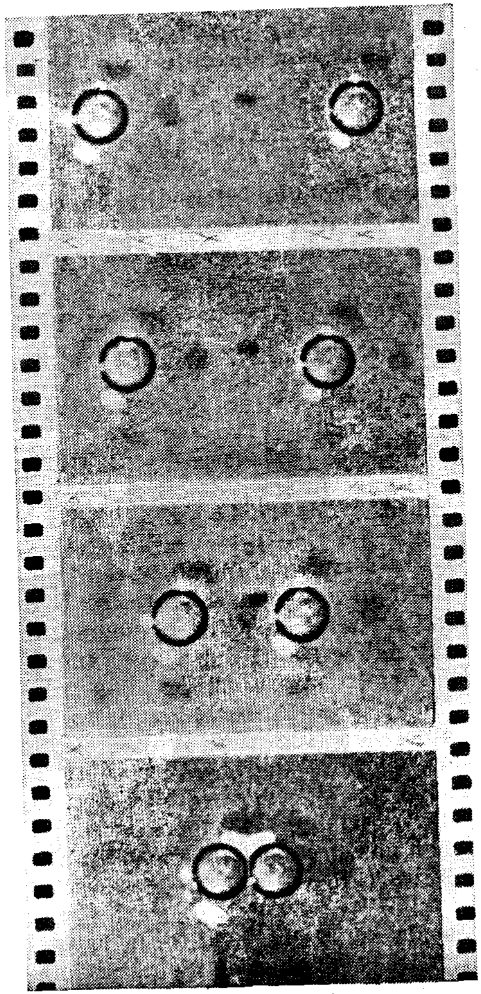

Fig. 73

simply one or two. If the radius of a bubble is $R = 5 \times 10^{-2}$ cm, then $N \sim (R_p/R)^2 \sim 4 \times \times 10^4$ bubbles can fit on the surface of a soap solution on an ordinary dinner plate whose radius is $R_p \approx 10$ cm. Such a raft of bubbles, contained by attractive and repulsive forces, is a two-dimensional model of crystal. The authors of this very beautiful model have shown, for example, that bubbles whose radius is $R \sim 10^{-1}$ cm

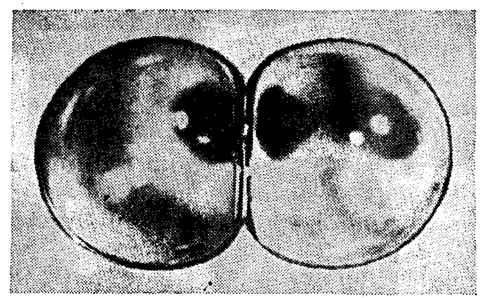

Fig. 74

interact very similarly to atoms in copper crystals.

The Model in Action

The film of the BLN model in action is interesting since it shows an ideal crystal, a crystal with moving and interacting defects, and many other simple and complex processes that develop in a real crystal. In an article, however, it is only possible to show a few photographs to illustrate the possibilities of the model.

The BLN model can be used to verify certain corollaries to the theory of crystal that is absolutely free of defects, i.e. the so-called ideal crystal. It is almost impossible to obtain such a crystal in nature, but it proved rather simple and easy to construct one made of bubbles (Fig. 75).

One of the most common defects in crystal is a vacant position at a point in the lattice, which is not filled by an atom. Physicists call this phenomenon a vacancy. In the BLN model a vacancy is represented by an exploded bubble (Fig. 76). As both common sense and experiments with real crystals lead us to expect, the BLN model shows that the volume of a vacancy is a little less than that of an occupied position. When a bubble explodes, neighbouring bubbles move slightly into the hole left by the explosion and reduce its size. This is almost impossible to detect with the naked eye, but if we project a photograph of the bubbles onto a screen and carefully measure the distances between bubbles, we can see that the vacancy is somewhat compressed in comparison with an occupied position. For physicists this is evidence of both a qualitative and a quantitative change.

Very often, crystal contains an impurity, introduced in the early stages of its history, that deforms its structure. To solve many problems of crystal physics, it is very important to know how the atoms surrounding the impurity have changed position. Incidentally, the presence of an impurity is left not only by the nearest neighbours but also by the atoms a considerable distance from it. The BLN model reflects this clearly (Fig. 76).

Most crystalline bodies are represented by po-

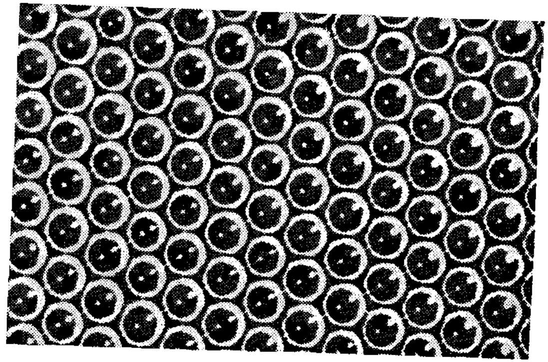

Fig. 75

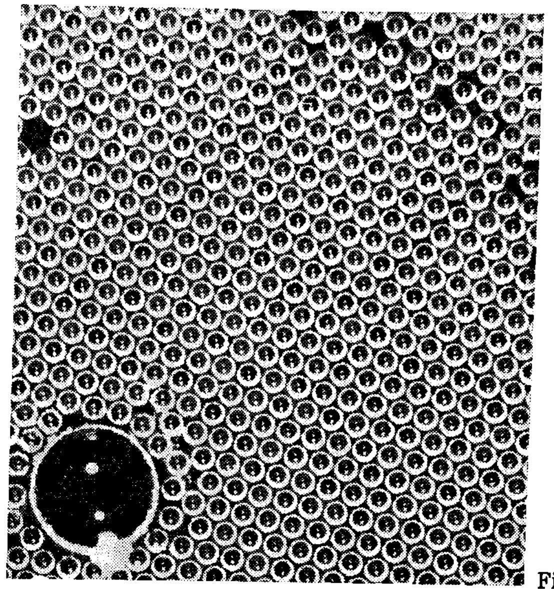

Fig. 76

lycrystals made of many small, randomly oriented crystals separated by boundaries. We expect many properties of the polycrystals (such as mechanical strength or electrical resistance) to depend on the structure of the boundaries, and, in fact, the BLN model bears this out. It showed crystal physicists that the structure of such boundaries varies according to the mutual orientation of boundary crystals, the presence of impurities at the boundary, and many other factors. Some parts of the polycrystals (grains), for example, may enlarge at the expense of others. As a result, average grain size increases. This process, called recrystallization, develops for a very explicit reason: the greater the size of the grain, the less its total boundary surface area, which means that it has lower excess energy linked to the boundaries. The energy of a polycrystal is reduced in recrystallization, and, therefore, the process may occur spontaneously (since it moves the system to a more stable equilibrium, at which energy storage is minimal). The series of photographs in Fig. 77 illustrates a large grain 'devouring' a smaller grain inside it in successive stages.

The moving boundary between the grains appears to 'swallow' the vacancies it comes across (this was predicted by theorists and carefully studied by experimenters in real crystals). The boundary does not change its structure in this process, as the BLN model clearly illustrates (Fig. 78).

Restrictions of the BLN Model

Without depreciating the usefulness of the BLN model, we should point out that it does

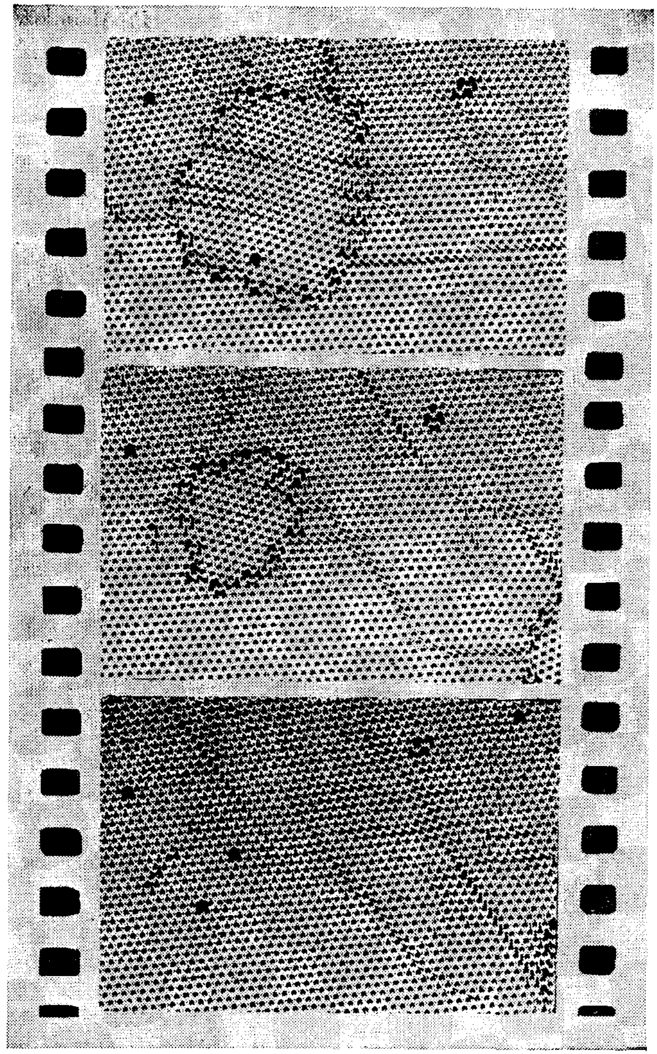

Fig. 77

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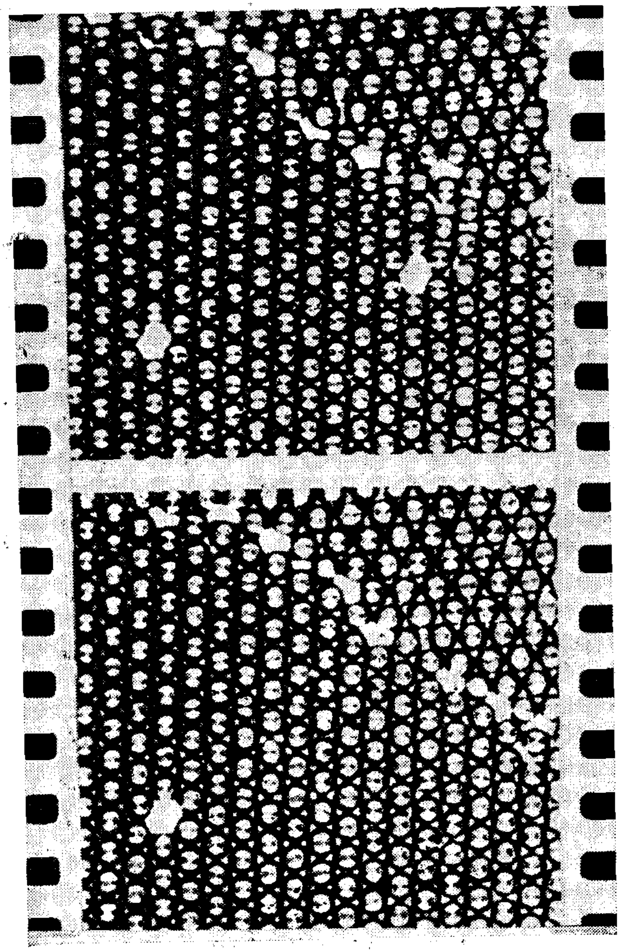


Fig. 78

have drawbacks. The model can simulate only one structure—a two-dimensional, hexagonal, and closely packed crystal. But real crystals have a variety of structures. In this respect, the dead model has infinitely more potential because atoms can be arranged in it in many different ways, and, consequently, any structure can be simulated. The BLN model in its contemporary modification is severely restricted by its two-dimensionality. Its authors tried to make a three-dimensional (multilayer) bubble model, but its operation was difficult, and the model was finally rejected. In our laboratory we built both two- and three-dimensional models and found the latter to be impractical. Despite these and other weaknesses, however, the BLN model is an indispensable aid in the study of crystals.

Determining the Poles of a Magnet

by B. Aleinikov

At first glance it may seem simple to determine the poles of a magnet. But because we cannot be sure that the poles of a given magnet have not simply been painted to make them look different, i.e. without reference to their true magnetism, the question is more complicated than it appears. Occasionally, magnets are not marked at all, in which case we need a method to differentiate the positive from the negative pole. For this experiment, we need a permanent horseshoe magnet (the poles need not be marked; in fact, it is even more challenging if they are not) and ... a television set. It is best to conduct the experiment in the daytime, when a test pattern for tuning the television is broadcast.

Turn the television set on, and put your magnet against the screen, as shown in Fig. 79. The image will immediately become distorted. The small circle in the center of the test pattern will

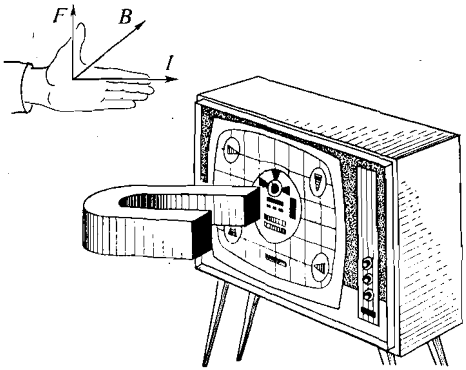


Fig. 79

shift noticeably upward or downward, depending on the position of the poles.

An image on the television screen is produced by an electron beam directed from inside the picture tube towards the viewer. Our magnet deviates the electrons emitted, and the image is distorted. The direction in which the magnetic field deviates the moving charge is determined by the left-hand rule. If the palm is positioned so that the lines of force enter it, the fingers when extended indicate the direction of the current. In this position, the thumb when held at a right angle to the fingers, will show the direction in

which the moving charge is deviated. The lines of force go from the northern to the southern pole of the magnet. The direction of current according to the left-hand rule is the so-called "technical" direction from plus to minus in which positively charged particles would move. In the cathode tube, however, the electrons move and are directed towards us. This is the equivalent of positive charges heading away from us. Therefore, the extended fingers of the left hand should be directed towards the screen. The rest is clear. By the displacement of the central circle, we can determine whether the northern or the southern pole of the magnet been placed against the screen.

It is also possible to identify poles of an unmarked battery with the help of a television. For this experiment, in addition to a television, we need a battery, an electric magnet with an arched core, a resistor, and a conductor. Connect the battery in series to the electromagnet, and the resistor, rated to limit the current to admissible level. Hold the electromagnet near the screen, and identify its poles using the left-hand rule. Then use the corkscrew rule to determine the direction of the current and, consequently, the poles of the battery.

A Peculiar Pendulum

by N. Minz

The familiar simple pendulum does not change the plane in which it swings. This property of the pendulum was used in a well-known demonstration of the Earth's rotation, i.e. the Foucault pendulum. The pendulum suspended on a long wire oscillates. A circle under it is marked as a clock face. Since the plane of oscillations relative to the motionless stars does not shift, while the Earth rotates on its axis, the pendulum passes through markings on the clock in succession. At either of the Earth's pole, the circle under the

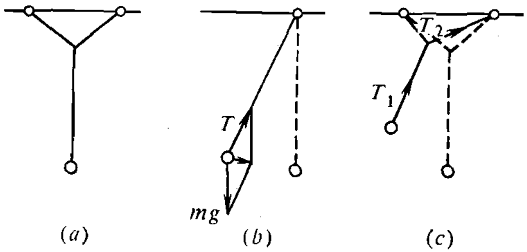


Fig. 80

pendulum makes one complete rotation in twenty-four hours. This experiment was carried out by the French physicist L. Foucault in 1851, when a pendulum 67 metres long was suspended from the cupola of the Pantheon in Paris.

Do all pendulums keep the same plane of oscillation? The suspension, after all, allows oscillations in any vertical plane. To make the pendulum shown in Fig. 80*a*, fold a string in half, and attach another string in the middle. Tie the loose end of the second string to a spoon, a pair of scissors, or any other object, and your pendulum is ready. (The vertical suspension should be longer or at least equal in length to that of the first string.)

Tack the ends of the horizontal string between the jambs of a doorway. Now, pull the pendulum back (at rest, it is in the position of equilibrium), and release it. The pendulum will describe an ellipse that constantly changes shape, prolating to one side or the other. Why does it behave this way?

A single suspension pendulum (Fig. 80*b*) has an undetermined plane of oscillation. This means that regardless of the initial deviation of the pendulum, all the forces influencing it lie in one plane. Be careful, however, not to propel it sideways when setting it free.

Now let us draw a plane through the initial and deviated positions of the pendulum. Obviously, both the gravity force mg, and the tension force of the string T lie in this plane. Consequently, the resultant of the two forces, which makes the pendulum oscillate, acts in the same plane. Thus, since there is no force to propel the pendulum out of the plane, it keeps its plane of oscillation.

Our pendulum is quite another thing. In this case, the initial plane of oscillation is determined by the attachment of the horizontal string and by the plumb line of the vertical string. Therefore, the pendulum is deviated from the very beginning so that it lies outside of the plane.*

The tension force (Fig. 80*c*) has a component perpendicular to the initial plane, and the ac-

* Of course, if the deviation of the pendulum in the plane is strictly perpendicular to the plane of suspension, the pendulum will oscillate in this plane only. In practice, however, a departure from this plane and velocity directed away from the plane always exist.

tion of this component forces the pendulum out of the plane. Since the tension force varies, its perpendicular component also varies. As it swings to the opposite side, the pendulum pulls the other half of the horizontal string taut. This develops a force that acts in the opposite direction. At the

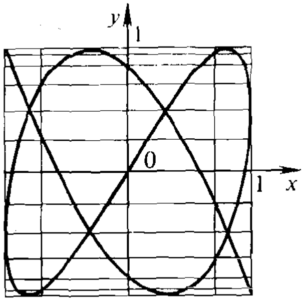


Fig. 81

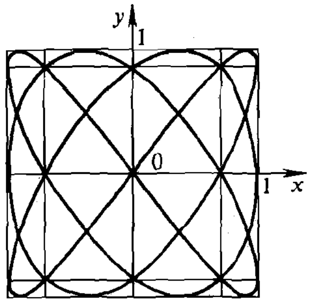


Fig. 82

same time, as the experiment shows, the pendulum oscillates in two perpendicular planes.

The curves described by our pendulum are called Lissajous figures, after the French physicist who was the first to describe them in 1863. A Lissajous figure results from the combination of two perpendicular oscillations. The figure may be rather complicated, especially if the frequencies of longitudinal and latitudinal oscillations are close. If the frequencies are the same, the resultant trajectory will be an ellipse. Figure 81 shows the figure drawn by a pendulum whose motion can be described as $x = \sin 3t$, $y = \sin 5t$. Figure 82 shows the oscillations described as $x = \sin 3t$, $y = \sin 4t$.

The ratio of the frequencies can be varied by varying the ratio of the length of the vertical and horizontal strings. Although it is fairly difficult to calculate the frequencies of pendulum oscillations, the figures drawn by the pendulum can be demonstrated rather easily. To make the Lissajous figures visible, tie a mall bucket with

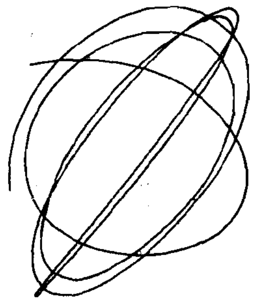


Fig. 83

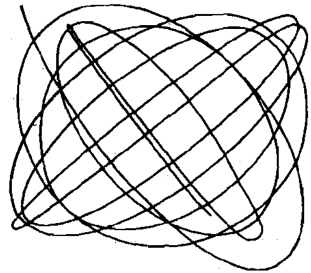


Fig. 84

a perforated bottom to the pendulum. Fill the bucket with sand, and put a piece of dark cardboard under it on the floor. The pendulum will draw a clear trajectory of its motion.

Photographs of the motion of the pendulum can also be made. Paint a weight or a small, heavy ball white, and make the suspension of dark string. Put a sheet of dark paper on the floor, the paper should be mat, since glossy paper reflects light and would spoil the pictures. Set the camera above the pendulum, with the lens placed horizontally. If the exposure is long enough, the pictures will show clear trajectories. Figures 83 and 84 show trajectories photographed in this way.

Changes in the direction of the oscillations are obvious. The change is especially sudden in Fig. 83. The exposures of the two photographs were different, which is obvious from the different lengths of the trajectories. The curves seem to be inscribed within a parallelogram, although in reality, they should be inscribed within a rectangle. We did not get a rectangle simply because the plane of our camera was not strictly horizontal.

A reasonably correct trajectory can be obtained in experiments with a pendulum if damping is insignificant. The oscillations of a pendulum with low mass and large volume will damp quickly. Such a pendulum will swing several times with quickly diminishing amplitude. Naturally changes in the oscillations of a pendulum with such strong attenuation can hardly be photographed.

Lissajous figures are common with perpendicular oscillations. They are unavoidable, for instance, in tuning oscillographs.

Lissajous Figures

by N. Minz

The simplest oscillations of a body are those in which the deviation of the body from its equilibrium position x is described as

$$x = a \sin (\omega t + \varphi)$$

where a is the amplitude, ω is the frequency, and φ is the initial phase of oscillation. Such oscilla-

tions are called harmonic. A simple pendulum, a weight on a spring, or voltage in an electric circuit can oscillate harmonically.

In this article we shall discuss a body with two simultaneous harmonic oscillations. If both oscillations occur along the same straight line, the re-

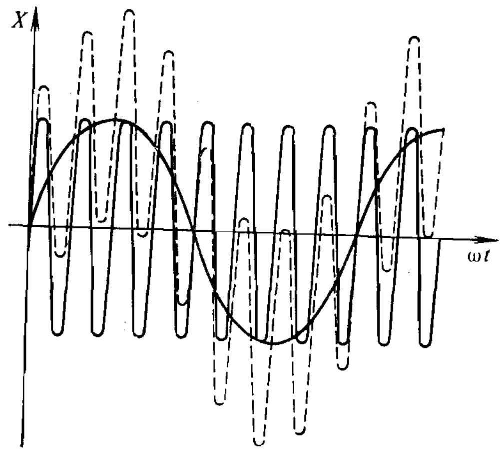


Fig. 85

sultant equation of the motion of the body will be a sum of the equations of each motion:

$$x = A_1 \sin (\omega_1 t + \varphi_1) + A_2 \sin (\omega_2 t + \varphi_2)$$

It is easy to make a graph of the body displacement from equilibrium over time. For this, the ordinates of the curves related to the first and second motions should be added. Figure 85 illustrates how two harmonic oscillations can be added (solid sinusoids). The broken line represents the resulting oscillation, which is no longer harmonic.

More complicated trajectories appear if two mutually perpendicular oscillations are added. The body in Fig. 86 moves along such a trajectory. Its form depends on the ratios of frequencies, amplitudes, and phases of the two mutually perpendicular oscillations. As we know, such trajectories are called Lissajous figures. The setup used by Lissajous in his experiments is shown in Fig. 87. The tuning fork T' oscillates in a horizontal plane, whereas T is vertical. A light beam passing through a lens is reflected by a mirror attached to T' towards a second mirror fixed on T. The reflection of the second mirror is seen on a screen. If only one tuning fork oscillates, the light spot on the screen will move along a straight line. If both tuning forks oscillate, the spot will draw intricate trajectories.

The trajectory of a body with two simultaneous, mutually perpendicular oscillations is described by a system of equations

$$\left.\begin{aligned} x &= A_1 \sin(\omega_1 t + \varphi_1), \\ y &= A_2 \sin(\omega_2 t + \varphi_2), \end{aligned}\right\} \qquad (1)$$

where x and y are the projections of the body displacement on X and Y axes.

For simplicity, assume $\varphi_1 = \varphi_2 = 0$ and $\omega_1 = \omega_2 = \omega$. Then

$$\left.\begin{aligned} x &= A_1 \sin \omega t, \\ y &= A_2 \sin \omega t. \end{aligned}\right\} \qquad (2)$$

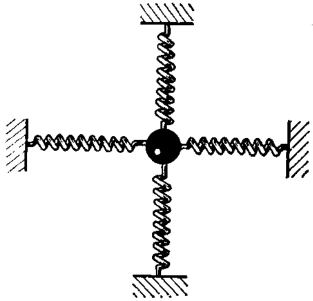


Fig. 86

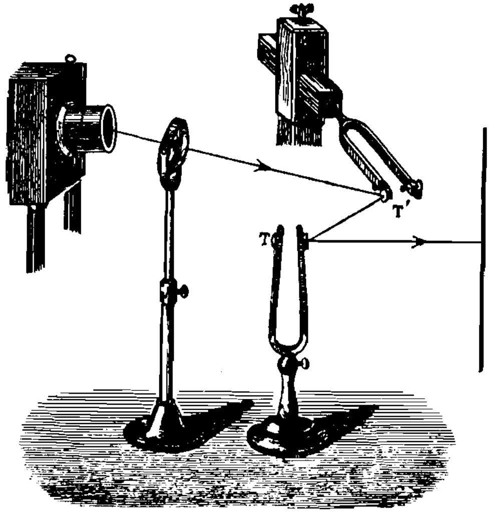


Fig. 87

Thus, $y = \frac{A_2}{A_1} x$. Consequently, Eq. (2) describes a straight line segment. Slope α with respect to X axis is

$$\tan \alpha = \frac{A_2}{A_1}.$$

Now let $\varphi_1 = \varphi_1' + \frac{3\pi}{2}$. Then

$$\left.\begin{aligned} x &= A_1 \cos(\omega_1 t + \varphi_1'), \\ y &= A_2 \sin(\omega_2 t + \varphi_2). \end{aligned}\right\} \qquad (3)$$

Consider first the simplest case, where $A_1 = A_2$, $\varphi_1' = \varphi_2 = 0$ and $\omega_1 = \omega_2 = \omega$, that is

$$\left.\begin{aligned} x &= A \cos \omega t, \\ y &= A \sin \omega t. \end{aligned}\right\} \qquad (4)$$

A point with x and y coordinates determined by the above equations makes a circle of A radius. And, in fact, $x^2 + y^2 = A^2 \cos^2 \omega t + A^2 \sin^2 \omega t = A^2$, which means that the trajectory of motion is a circle.

Now let $A_1 \neq A_2$. Let us plot a trajectory for $A_1 = 1$ and $A_2 = 2$. At the moment of maximal displacement, $x = A_1 = 1$, that is, $\cos \omega t = 1$, $\omega t = 0$. Consequently, $y = 2 \sin \omega t = 0$. Similarly, when $x = 0$, y equals two, and when $x = \frac{\sqrt{2}}{2}$, y equals $\sqrt{2}$, and so on.

The graph plotted with these coordinates will be an ellipse whose major semiaxis is A_2 and

whose minor semiaxis is A_1, that is, the ellipse elongated along Y axis (Fig. 88*a*).*

It is easy to show that when $A_1 = 2$ and $A_2 = 1$, we get an ellipse elongated along X (Fig. 88*b*). Clearly, by changing the amplitude ratio, we can get different ellipses.

Now let $\omega_1 = 2\omega$, $\omega_2 = \omega$, $\varphi_1' = 0$ and $\varphi_2 =$

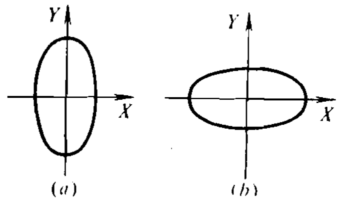


Fig. 88

$= 0$. The system of equations (3) will then become

$$x = A_1 \cos 2\omega t,$$
$$y = A_2 \sin \omega t.$$

Transform the equation with respect to x in the following way

$$x = A_1 (\cos^2 \omega t - \sin^2 \omega t) =$$
$$= A_1 (1 - 2 \sin^2 \omega t) = A_1 \left(1 - 2 \frac{y^2}{A_2^2}\right).$$

* The fact that the system of equations

$x = A_1 \cos \omega t$
$y = A_2 \sin \omega t$

describes an ellipse can be shown analytically:

$$\frac{x^2}{A_1^2} + \frac{y^2}{A_2^2} = \cos^2 \omega t + \sin^2 \omega t = 1,$$

i.e., a point with coordinates x and y lies on the ellipse.

This curve is part of a parabola with its axis along X and the apex at $x = A_1$ (Fig. 89). Thus, we have an open curve.

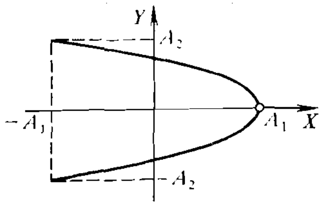


Fig. 89

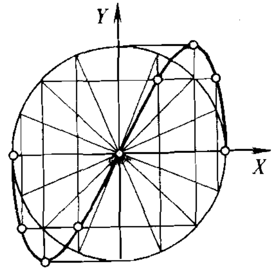


Fig. 90

Now let us check the effects of the frequency on the shape of the trajectory. We will assign equal amplitudes to the lateral and longitudinal oscillations described by system (3).

Let us plot curves, for example, described by the following equations:

$$x = A\cos\omega t,\ y = A\sin 2\omega t,$$
$$x = A\cos\omega t,\ y = A\sin 4\omega t.$$

The easiest way to do this is to draw a circle of A radius (Fig. 90) and mark the points corresponding to angles ωt, which equal $0, \frac{\pi}{8}, \frac{\pi}{4}, \frac{3\pi}{8}, \frac{\pi}{2}, \frac{5\pi}{8}, \frac{3\pi}{4}, \frac{7\pi}{8}, \pi, \ldots, 2\pi$. To determine the points with coordinates $x = A\cos\omega t$ and $y = A\sin 2\omega t$, remember that for the circle whose radius is equal to unity ($r = 1$) the $\cos\omega t$ is numerically equal to a projection of the vector radius $r(\omega t)$

onto X, whereas the $\sin\omega t$ is equal to the projection onto Y. Since we have drawn a circle of A radius, the coordinates x and y of each point of the circle are the projections of the vector radii

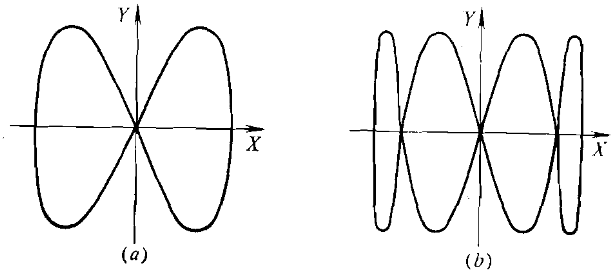


Fig. 91

of the points onto X and Y. Once we have determined all the points by their coordinates, we can connect them with a solid line (Fig. 90).

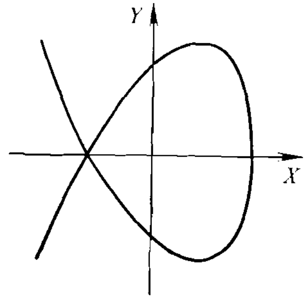


Fig. 92

In both cases we obtain closed curves, whose loop number is defined by the ratio $n = \frac{\omega_2}{\omega_1}$ (Fig. 91a, b).

The figure in Fig. 92 is open. It is described by the following system of equations

$$x = \cos 2\omega t,$$
$$y = \sin 3\omega t.$$

When do open figures occur? Are there any common regularities in their origin? Consider the following equations

$$x = A_1 \cos p\omega t,$$
$$y = A_2 \sin q\omega t.$$

First, note that at the point where the curve reverses along the same trajectory, the velocities of the body along the X and Y axes become equal to zero simultaneously. The body moving along the curve stops at exactly this moment and then starts moving back. If $x = A_1 \cos p\omega t$, then

$$v_x = \frac{A_1 \cos p\omega t_2 - A_1 \cos p\omega t_1}{t_2 - t_1} =$$
$$= \frac{-2A_1 \sin \frac{p\omega t_2 + p\omega t_1}{2} \sin \frac{p\omega t_2 - p\omega t_1}{2}}{t_2 - t_1}$$

When $t_2 \approx t_1 = t$ (the difference between t_2 and t_1 is small),

$$\sin \frac{p\omega t_2 - p\omega t_1}{2} \approx \frac{p\omega t_2 - p\omega t_1}{2}.$$

As a result,

$$v_x = -A_1 p\omega \sin p\omega t.$$

Similarly, for v_y

$$v_y = A_2 q\omega \cos q\omega t.$$

When the velocities v_x and v_y are equal to zero,

$$v_x = 0 \quad \text{if} \quad p\omega t = k\pi,$$
$$v_y = 0 \quad \text{if} \quad q\omega t = \frac{\pi}{2} + m\pi.$$

From these conditions it becomes obvious that Lissajous figure are open when

$$\frac{p}{q} - \frac{2k}{2m+1}.$$

The curve in Fig. 92, for example, meets this condition.

Lissajous figure can be observed on the screen of an oscilloscope. A vertical sweep indicates one harmonic oscillation, whereas another oscillation appears on a horizontal sweep. Their total may assume different forms if the frequency of the alternating voltage at the plate of the oscilloscope is varied.

Anyone can make a simple device for observing and photographing Lissajous figures. Twist a simple metal ruler so that the plane of one half of the ruler is perpendicular to the plane of the other half. Fix one of the ends of the ruler in a bench vice. When the free end is depressed and then released, it will draw intricate Lissajous figures in the air.

The motion of the free end of the ruler is the sum of the independent oscillations of its two parts. The first section is measured from the vice to the bend in the ruler and the second from the bend to the free end. The oscillation of each part is perpendicular to the plane of the vibrating section. Since the bend angle of the ruler is $\frac{\pi}{2}$, the oscillations are mutually perpendicular. The shape of the trajectory of the end depends on the length and the width of the ruler, as well as on the place of bend.

The same ruler can be used to obtain different figures, to vary vertical and horizontal oscillation ratios, simply clamp the ruler at different places. Since the frequency of oscillations depends on the length of the ruler, you can vary the fre-

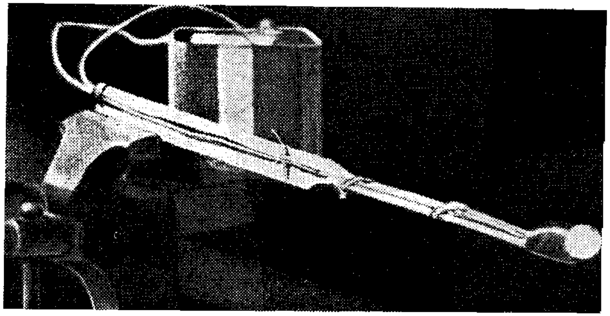


Fig. 93

quency ratio of mutually perpendicular oscillations of the end of the ruler by changing the ratio of the length of its parts. This will result in different trajectories of the end.

To photograph the figures, attach the light bulb from a flashlight to the free end of the ruler. Connect the bulb to a battery by wires placed along the ruler (see Fig. 93). Place this complex pendulum in a dark room, and experiment a few times to find the right exposure time for photographs. A fairly long exposure will probably

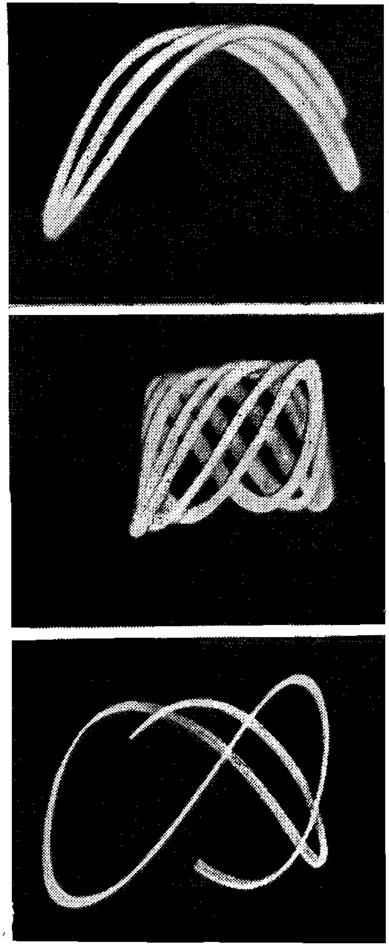


Fig. 94

work best. Figure 94 shows photograph obtained exactly in this way.

Now try similar experiments for yourself.

EXERCISES

1. Prove that all curves described by the following system of equations are open:

$x = A_1 \cos p\omega t, \quad y = A_2 \cos q\omega t$

2. Derive an equation for a curve with the following parameters

$x = A_1 \cos \omega t, \quad y = A_2 \cos 2\omega t$

Waves in a Flat Plate (Interference)

by A. Kosourov

Wave propagation is perhaps the most universal phenomenon in nature. Water, waves, sound, light and radio, even deformation transfer from one part of a solid to another are examples of this phenomenon. According to quantum mechanics, the motion of microscopic particles is also controlled by the laws of wave propagation. The physical nature, velocity of propagation, frequency and wavelength of all these waves are different, but despite these differences, the motion of all waves is similar in many respects. The laws of one kind of wave motion can be applied almost without modification to waves of another nature. The most convenient way to study these laws is to study waves on the surface of a body of water.

What is a wave? Throw a stone into a pond. The calm horizontal surface of the pond will develop circles that ripple outwards. Points on the surface of the water reached by the wave will begin to oscillate relative to the position of equilibrium, which corresponds to the horizontal surface of the water. The farther a point is from the centre of the circle, the longer the point will take to 'learn' about the stone that has been thrown. The disturbance travels at a determinate speed. Points that are reached simultaneously by the disturbance are said to be in the same stage or phase of oscillation.

All waves disturb some physical object with their action by causing the object to deviate from the state of equilibrium. Sound waves, for example, cause the periodic rise and drop of pressure. Radio waves and light cause rapid changes of tension in electric and magnetic fields. The properties of all media without exception are such that a disturbance, which originates in a specific area, propagates by passing from one point to another with a final speed. This speed depends on the nature of the disturbance and the medium.

The disturbance that generates a wave must have a source, that is an external cause that breaks the equilibrium in a certain area of the medium. A small disturbance, a stone thrown into water, for example, radiates spherical waves (in this case, circles on the water surface) that travel radially in a uniform medium (a medium in which wave velocity does not depend on the direction of its propagation). Such sources are called point sources.

One of the main principles of elementary wave theory is the principle of wave independence, also called the principle of superposition. The principle states that a disturbance caused by a wave at a point of observation is not influenced by other waves passing through the same point. The principle of superposition is, in fact, a simple rule for determining the summary effect of waves from different sources. A summary oscillation is simply a sum of the oscillations caused by each source independently.

Interference is a characteristic feature of wave processes. Interference is the combination of phenomena that develop in a medium in which waves propagating from two or more sources oscillate synchronously. The oscillations of some points of the medium may be stronger or weaker under the action of the two simultaneous sources than they would be under the effect of either source in isolation. Synchronized waves may even suppress each other completely.

Let us try to produce interference that we can see with our own eyes. An experienced observer can easily see the interference caused by the waves from two stones thrown into a pond. This method is unsuitable for study of interference, however. We need, instead, a stable picture of interfering waves in the laboratory.

The first thing we will need for this experiment is a vessel for water. The vessel should have gently sloping walls to avoid masking waves from the source with reflections from the walls. A shallow saucer will work well, if the water nearly reaches the rim, in which case the waves roll onto the walls and are damped quickly, almost

without reflections. An electric bell without its cap is a good wave generator. Wire the hammer of the bell, and attach a cork ball to the wire. This cork will be our wave source. Be sure that the electric wires are well insulated.

The bell should be mounted on a swing above the saucer so that it can be lowered into the water at the rim of the saucer. Power should be furnished by an autotransformer, which will enable us to vary the amplitude of the oscillations. The autotransformer from either a toy electric train or an electric burning-out machine will serve this purpose. When we switch on the setup, we will see circular waves on the water surface. The average distance between neighbouring crests, that is, the wavelength, will be about 1 cm (Fig. 95).

The waves can best be observed by watching the shadows on the bottom of the saucer under direct sunlight or strong lamplight. Every wave acts like a cylindrical lens and casts a bright band on the bottom that repeats the configuration of the wave front. Since the waves move at about 10 centimetres per second, however, they may seem to merge if you keep your eyes fixed on the plate. They are visible only close to the source where their amplitude is high, and you will need to turn your head quickly to trace individual waves on the surface, just as you would need to move your head rapidly to trace the motion of individual spokes in a rotating wheel. The waves are very clear on the mat plate of a camera, especially one with a large format. By holding such a camera by hand and rocking it gently, you can easily find a position from which the waves, which appear to move very slowly can be seen over the entire surface. A mirror can also be used to watch the water surface. The most expedient way to observe the waves is with a stroboscope. If we illuminate the setup with short flashes of

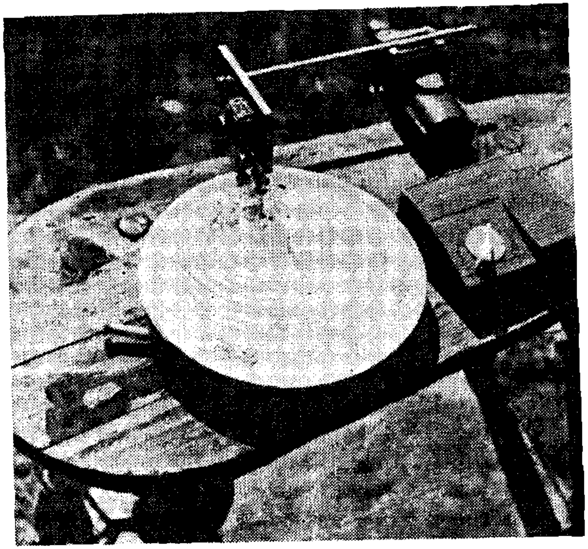


Fig. 95

light with the same frequency as the wave generator, the wave will move over one wavelength from one flash to the next, and as a result, the wave picture will appear stationary. To obtain this effect, simply wire a small lamp into the circuit, parallel to the electric bell magnet winding. At a distance of 0.5-1 m, the lamp will illuminate

the saucer uniformly, and the stationary wave picture will appear clearly. It is better to use direct sunlight for photographs.

Now replace the single cork ball on the hammer of the bell with a wire fork to which two pieces of cork have been attached at the ends. The distance between the ends should be 2-3 cm. If the corks touch the water surface simultaneously, you will get two sources of waves that oscillate not only synchronously, i.e. in time, but in phase, which means that the waves from the two sources will appear in the same instance of time. The picture will look approximately like in Fig. 96 (here $2d/\lambda = 4$). The fan-shaped distribution of high-amplitude zones includes intermittent 'silence' zones. The central zone of high amplitudes is perpendicular to the line connecting the sources, and both types of zones are located between the sources.

According to the interference picture, the distance between neighbouring peaks on the line connecting the sources is one-half of the distance between two crests, that is, one-half of a wavelength. If we change the distance between the sources, the number of high-amplitude zone will change too. In Fig. 97 the characteristic ratio is $2d/\lambda = 2$. The larger the distance between sources, the more 'feathers' we have in our fan. But the distance between crests on the line connecting the sources is always one-half of a wavelength. Thus, the total number of high-amplitude zones will always be twice the number of wavelengths in the distance between sources. Hence, we can conclude that if this distance is less than one-half of a wavelength, the waves will not inter-

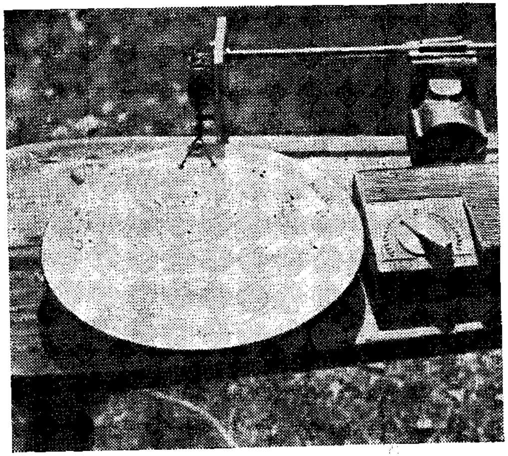


Fig. 96

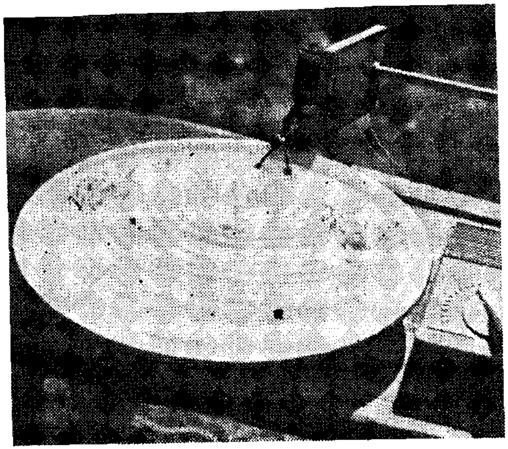


Fig. 97

fere at all. Such sources act as one, producing a single system of circular waves. This can be demonstrated by gradually reducing the distance between sources. Note also that if a wavefront continues from a high-amplitude zone to a neighbouring zone, it will pass from a crest to a trough. In other words, as a wave passes through the zero phase, the phase of the wave changes by one-half of a complete cycle.

Now imagine that instead of two cork balls creating waves in the water we have two light sources emitting light waves. If we place a screen perpendicular to the water surface in the path of the lightwaves, we will see illuminated places, which indicate high-amplitude zones, and shadows. Now let us try to explain these dark and light interference bands.

Draw the two wave systems on paper, as if the waves were frozen in their tracks (Fig. 98). Indicate the crests with light, solid lines and the troughs with broken lines. Assign every wave a number, giving identical numbers to those that originate from the sources simultaneously. As is clear from the drawing, waves with the same number covered the distance equivalent for both sources simultaneously. Obviously, this occurs because all points at this distance are reached by waves that travel the same distance. By applying the law of superposition, we can conclude that the heights of the crests and depths of the troughs will double at this distance. The resulting crests should be marked in the drawing with heavy, solid lines; mark the troughs with heavy, broken lines. To the right and left of line 00 are points at which the crests of one system of waves coincide with the troughs of another. The waves from one source cause upward deviation at these points, while the waves from the second source cause downward deviation, and, as a result, to-

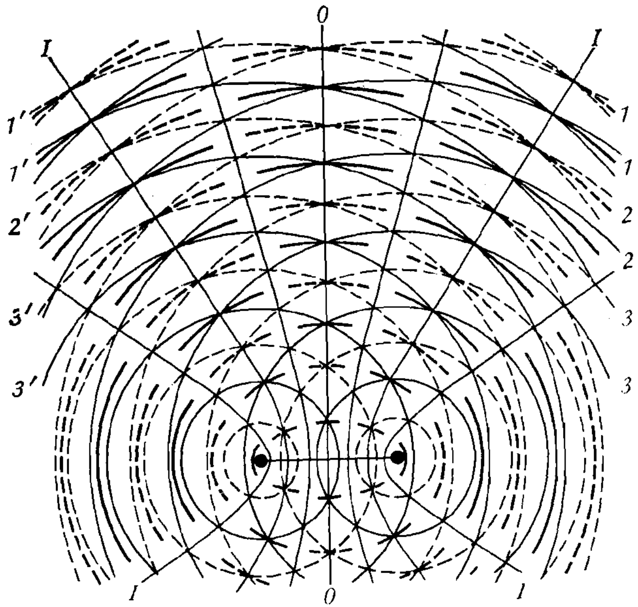


Fig. 98

tal deviation is close to zero. Connect all such points with a solid line. If we analyse the numbers of the crests and troughs, we will see that all the points of the right line are reached by waves from the left, which travel half a wavelength farther than waves from the right.

To the right and left of the zero lines lie the points of intersection of the first crest with the second, the second with the third, and so on. It is easy to see that these are maxima points. If we connect these points, we get a line that is reached by one wave system with the delay of one wavelength.

By analysing the drawing further we can find all the zero and maxima lines. Such lines are hyperbolas.

It is now clear why the distance between neighbouring maxima on the line connecting the sources equals one-half a wavelength. Indeed, the midpoint of this line is reached by waves of the two systems, which move in the same phase and enhance one another. If we move off the point by one-half a wavelength, the distance travelled by one wave will increase by one-half a wavelength, whereas the distance covered by another will decrease by the same value. The difference between the distances travelled by both waves will equal one wavelength, and the waves will enhance one another again. This will reoccur every half wavelength.

A maximum observed when the difference in the distance travelled is zero is called the zero maximum or the zero order of interference. Maxima observed when the distance is one wavelength are called first-order interference, and so on. A maximal order of interference is determined by the integer closest to $2d/\lambda$, where d is the distance between sources and λ is the wavelength. Now try to predict from the drawing or from experiments what changes will occur if one of the sources radiates waves with half a period (or a fraction of a period) delay. What will happen if the phase shift is random? To study this phenomenon experimentally, simply make the ends of the wire fork different lengths.

How to Make a Ripple Tank to Examine Wave Phenomena *

by C. L. Stong

Waves of one kind or another are found at work everywhere in the universe, ranging from gamma rays of minute wavelength emitted by nuclear particles to the immense undulations in clouds of dust scattered thinly between the stars. Because waves of all kinds have in common the function of carrying energy, it is not surprising that all waves behave much alike. They move in straight lines and at constant velocities through uniform mediums and to some extent change direction and velocity at junctions where the physical properties of the mediums change. The part of a sound wave in air that strikes a hard object such as a brick wall, for example, bounces back to the source as an echo.

By learning how waves of one kind behave the experimenter learns what behaviour to expect of others, and problems solved by the study of waves in one medium can be applied, with appropriate modification, to those in other mediums.

The pan of a simple ripple tank that can be made in the home consists of a picture frame *6*

* An abridged version of an article that first appeared in the November issue of *Scientific American* for 1962.

about five centimeters thick and 0.6 m^2 square, closed at the bottom by a sheet of glass calked to hold water, as shown in Fig. 99. The tank is supported about 60 cm above the floor by four sheet-metal legs. A source of light to cast shadows of

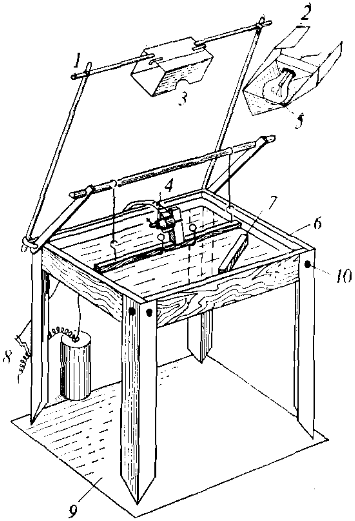


Fig. 99. Ripple tank for demonstrating wave behavior:
(*1*) dowels, (*2*) aluminized cardboard, (*3*) hole for light, (*4*) 1½-volt motor vibrator, (*5*) 100-watt bare straight filament lamp with filament vertical, (*6*) picture frame with glass bottom set in mastic, (*7*) paraffin reflector, (*8*) alligator clip and steel spring for adjusting motor speed, (*9*) white paper display screen, (*10*) slots for leveling

ripples through the glass onto a screen *9* below is provided by a 100-watt clear lamp *5* with a straight filament. Because the lamp is suspended above the tank with the filament axis vertical, the end of the filament approximates a point source and casts sharp shadows. The lamp, partly enclosed by a fireproof cardboard housing *2*, is suspended about 60 cm above the tank on a framework of dowels *1*. The wave generator hangs on rubber bands from a second framework made of a pair of metal brackets notched at the upper end to receive a wooden crossbar. The distance between the wave generator and the water can be adjusted either by changing the angle of the metal brackets or by lifting the crossbar from the supporting notches and winding the rubber bands up or down as required. The agitator of the wave generator

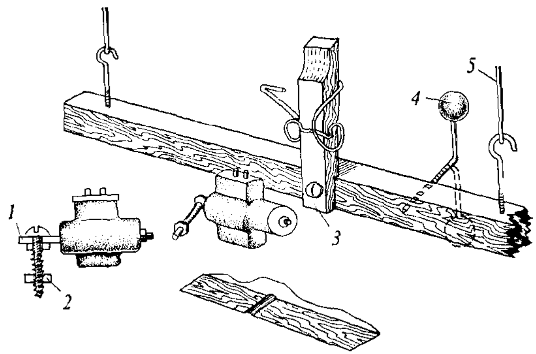


Fig. 100. Details of ripple generator:
(1) shaft passes through hole in screw, (2) eccentric weight for adjusting amplitude of oscillation, (3) $1^1/_2$-volt motor clamped in clothes-pin, (4) bead on wire can be turned down to give point source of waves, (5) rubber-band supports

erator is a rectangular wooden rod. A wooden clothespin *3* at its center grasps a 1.5 volt toy motor driven by a dry-cell battery. Several glass or plastic beads *4* are attached to the agitator by stiff wires, bent at right angles, that fit snugly into any of a series of holes spaced about five centimeters apart. Details of the wave generator are shown in Fig. 100. Attached to the shaft of the motor is an eccentric weight, a 10-24 machine screw about 2.5cm long. The shaft *1* runs through

a transverse hole drilled near the head of the screw, which is locked to the motor by a nut run tight against the shaft; another nut *2* is run partly up the screw. The speed of the motor is adjusted by a simple rheostat: a helical spring of thin steel wire (approximately No. 26 gauge) and a small alligator clip. One end of the spring is attached to a battery terminal, and the alligator clip is made fast to one lead of the motor. The desired motor speed is selected by clipping the motor lead to the spring at various points determined experimentally. (A 15-ohm rheostat of the kind used in radio sets can be substituted for the spring-and-clip arrangement.)

The inner edges of the tank are lined with four lengths of aluminium fly screening *1* 7.6 cm wide bent into a right angle along their length and covered with a single layer of cotton gauze bandage *2*, either spiraled around the screening as shown in Fig. 101 or draped as a strip over the top. The combination of gauze and screening absorbs the energy of ripples launched by the generator and so prevents reflection at the edges of the tank that would otherwise interfere with wave patterns of interest.

The assembled apparatus is placed in operation by leveling the tank and filling it with water to a depth of about 20 mm, turning on the lamp, clipping the motor lead to the steel spring and adjusting the height of the wave generator until the tip of one glass bead makes contact with the water. The rotation of the eccentric weight makes the rectangular bar oscillate and the bead bob up and down in the water. The height, or amplitude, of the resulting ripples can be adjusted by altering the position of the free nut on the machine screw. The wavelength, which is the distance between the crests of adjacent waves, can be altered by changing the speed of the motor. The amount of contrast between light and shadow in the wave patterns projected on the screen can be

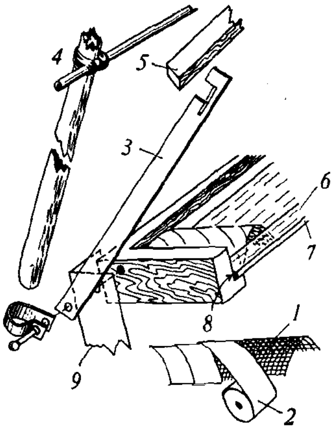


Fig. 101. Details of tank brackets and wave absorbers:
(1) wave absorber, fly screen, (2) gauze bandage, (3) strap iron, (4) support for light source, (5) support for wave generator, (6) water, (7) glass, (8) glass set in mastic calking compound, (9) 16-G aluminium legs

altered by rotating the lamp. The wave generator should be equipped with at least one pair of beads so that ripples can be launched from two point sources. Waves with straight fronts (analogues of plane waves that travel in mediums of three dimensions) are launched by turning the bead supports up and lowering the rectangular bar into the water.

As an introductory experiment, set up the generator to launch plane waves spaced about five centimeters from crest to crest. If the apparatus functions properly, the train of ripples will

flow smoothly across the tank from the generator and disappear into the absorbing screen at the front edge. Adjust the lamp for maximum contrast. Then place a series of paraffin blocks (of the kind sold in grocery stores for sealing jelly), butted end to end, diagonally across the tank at an angle of about 45 degrees. Observe how the paraffin barrier reflects waves to one side, as in Fig. 102(top). In particular, note that the angle made between the path of the incident waves and a line perpendicular to the barrier (θ_i) equals the angle made by the path of the reflected rays and the same perpendicular (θ_r). Set the barrier at other angles larger and smaller than 45 degrees with respect to the wave generator and also vary the wavelength and amplitude of the waves. It will be found that the angle of incidence equals the angle of reflection whatever the position of the barrier, a law of reflection that describes waves of all kinds.

Next replace the paraffin barrier with a slab of plate glass about 15 cm wide and 30 cm long and supported so that its top surface is about 12 mm above the tank floor. Adjust the water level until it is between 1.5 and 3.2 mm above the glass and launch a series of plane waves. Observe how the waves from the generator slow down when they cross the edge of the glass and encounter shallow water, as shown in Fig. 102 (bottom). As a result of the change in speed the waves travel in a new direction above the glass, just as a rank of soldiers might do if they marched off a dry pavement obliquely into a muddy field. In this experiment waves have been diverted from their initial direction by refraction, an effect

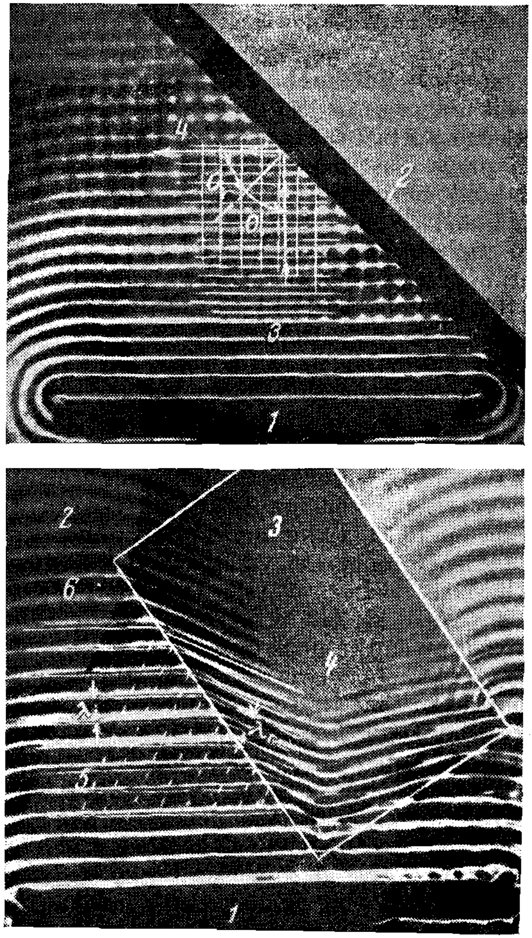


Fig. 102. Wave reflection and refraction:
top: (1) wave generator, (2) straight barrier, (3) incident waves, (4) reflected waves; bottom: (1) wave generator, (2) deep water, (3) shallow water, (4) refracted wave fronts, (5) reflected wave fronts, (6) incident wave fronts

observed in waves of all kinds when they cross obliquely from one medium to another in which they travel at a different velocity. Water waves are unique in that they travel at different speeds when the thickness, or depth, of the medium changes. To a very good approximation the ratio of wave velocity in shallow and deep water is proportional to the ratio of the depths of the

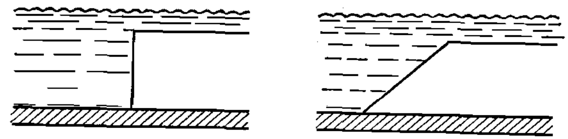


Fig. 103

water. This ratio is in effect the "index of refraction" of the two "mediums". In the case of electromagnetic waves (such as light) or mechanical waves (such as sound) the velocity of wave propagation varies with the density of the mediums.

The net reflection at the disjunction between the deep and shallow water can be minimized by beveling the edge of the glass (or any other smooth, solid material substituted for glass) as shown in Fig. 103.

Wave energy can also be focused, dispersed and otherwise distributed as desired by barriers of appropriate shape, as exemplified by the parabolic reflectors used in telescopes, searchlights, radars and even orchestra shells. The effect can be demonstrated in two dimensions by the ripple tank. Make a barrier of paraffin blocks or rubber hose in the shape of a parabola and direct plane waves toward it. At every point along the barrier the angle made by the incident waves and the perpendicular to the parabola is such that the reflected wave travels to a common point: the focus of the parabola. Conversely, a circular wave that originates at the focus reflects as a plane wave from the parabolic barrier, as shown *in Fig. 104* (top). *In this experiment* the wave was generated by a drop of water.

Interference effects can be demonstrated in the ripple tank by adjusting a pair of beads so that they make contact with the water about five centimeters apart. A typical interference pattern made by two beads vibrating in step with each other is shown in Fig. 104 (bottom). Observe that maximum amplitude occurs along paths where the wave crests coincide and that nodes appear along paths where crests coincide with troughs. The angles at which maxima and nodes occur can be calculated easily. The trigonometric sine of the angles for maxima, for example, is equal to $n\lambda/d$, where n is the order of the maximum (the central maximum, extending as a perpendicular to the line joining the source, is the "zeroth" order, and the curving maxima extending radially on each side are numbered "first", "second", "third" and so on consecutively), λ is the wavelength and d is the distance between sources. Similarly, minima lie along angular paths given by the equation $\sin \theta = (m - 1/2)\, \lambda/d$, where m is the order of the minima and the other terms are as previously defined.

Barriers need not be solid to reflect waves. A two-dimensional lattice of uniformly spaced pegs arranged as in Fig. 105 will reflect waves in

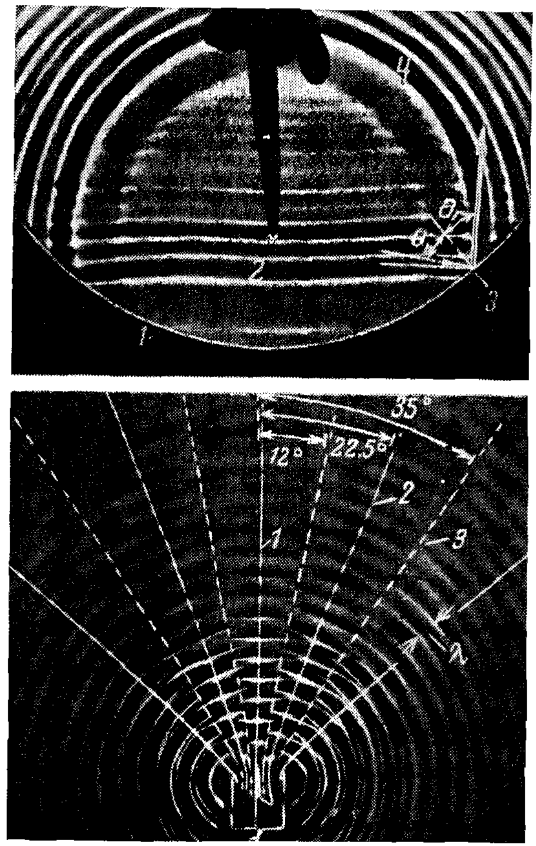


Fig. 104. Reflection from a parabolic barrier: top: (*1*) parabolic reflector, (*2*) reflected wave fronts, (*3*) normal to parabolic reflector, (*4*) incident wave fronts; bottom: (*1*) central maximum, (*2*) maximum, (*3*) node

the ripple tank that bear a required geometrical relation to the lattice. When a train of plane waves impinges obliquely against the lattice,

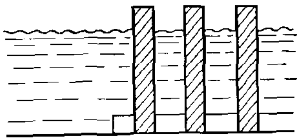


Fig. 105

circular waves are scattered by each peg and interfere to produce a coherent train of plane waves. The maximum amplitude of this train makes an angle with respect to the rows making

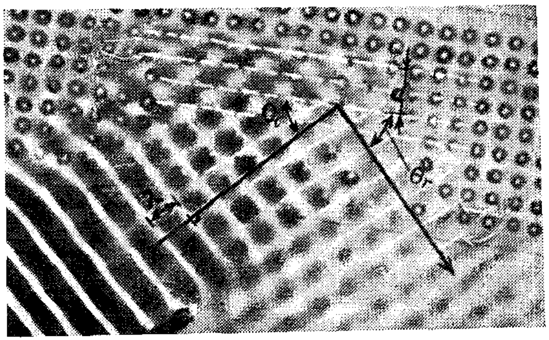


Fig. 106

up the lattice such that $\sin\theta \max = n\lambda/2d$, where $\sin\theta \max$ designates the direction of maximum wave amplitude, n the order, λ the wavelength and d the spacing between adjacent rows of pegs (the lattice spacing) (Fig. 106).

This equation, known as Bragg's law in honor of its British discoverers, the father-and-son team of Sir William Bragg and Sir Lawrence Bragg, has been widely applied in computing the lattice structure of crystal solids from photographs of wave maxima made by the reflection of X-ray waves from crystals.

Another of the many aspects of wave behavior that can be investigated with the ripple tank is the Doppler effect, first studied intensively by the Austrian physicist Christian Jahann Doppler. He recognized the similarity in wave behavior that explains the apparent increase in pitch of an onrushing train whistle and the slight shift toward the blue end of the spectrum in the color of a star speeding toward the earth. Both effects are observed because it is possible for moving wave sources to overtake and in some cases to outrun their own wave disturbances. To demonstrate the Doppler effect in the ripple tank, substitute for the agitator bar a small tube that directs evenly timed puffs of air from a solenoid-actuated bellows against the surface of the water while simultaneously moving across the tank at a controlled and uniform speed. (A few lengths of track from a toy train can be mounted along the edge of the tank and a puffer can be improvised on a toy car.)

When the puffer moves across the tank at a speed slower than that of the waves, crests in front of the puffer crowd closely together, whereas those behind spread apart, as shown in Fig. 106 (top).

The Doppler effect is observed in waves of all kinds, including radio signals. By means of relatively simple apparatus the effect can be applied to determine the direction and velocity of an artificial satellite from its radio signals.

These experiments merely suggest the many wave phenomena that can be demonstrated by the ripple tank.

Anyone who builds and operates a ripple tank will find it appropriate for enough fascinating experiments to occupy many rainy afternoons.

An Artificial Representation of a Total Solar Eclipse*

by R. W. Wood

In preparing for polarisation experiments on the solar corona, it is extremely desirable to have an artificial corona as nearly as possible resembling the reality. The apparatus described below is aimed at this end. The artificial corona in this case resembles the real so closely, as to startle one who has actually witnessed a total solar eclipse. The polarisation is radial, and is produced in the same way as in the sun's surroundings, and the misty gradations of brilliance are present as well. So perfect was the representation that I added several features of purely aesthetic nature to heighten the effect, and finally succeeded in getting a reproduction of a solar eclipse which could hardly be distinguished from the reality, except that the polar streamers are straight, instead of being curved, as all the recent photographs show them. The curious greenish-blue

* *Nature*, January 10, 1901, pp. 250-251.

colour of the sky, and the peculiar pearly lustre and misty appearance are faithfully reproduced. For lecture purposes an artificial eclipse of this sort would be admirably adapted, and I know of no other way in which an audience could be given so vivid idea of the beauty of the phenomenon. Drawings and photographs are wholly inadequate in giving any notion of the actual appearance of the sun's surroundings, and I feel sure that any one will feel amply repaid for the small amount of trouble necessary in fitting up the arrangement which I shall describe.

A rectangular glass tank about a 30 × 30 cm square on the front and 12 or 15 centimeters wide, and a six candle-power incandescent lamp are all that is necessary. The dimensions of the tank are not of much importance, a small aquarium being admirably adapted to the purpose. The tank should be nearly filled with clean water, and a spoonful or two of an alcoholic solution of mastic added. The mastic is at once thrown down as an exceedingly fine precipitate, giving the water a milky appearance.

The wires leading to the lamp should be passed through a short glass tube, and the lamp fastened to the end of the tube with sealing wax, taking care to make a tight joint to prevent the water from entering the tube (Fig. 107). Five or six strips of tinfoil are now fastened with shellac along the sides of the lamp, leaving a space of from 0.5 to 1 mm between them. The strips should be of about the same width as the clear spaces. They are to be mounted in two groups on opposite sides of the lamp, and the rays passing between them produce the polar streamers.

The proper number, width and distribution of the strips necessary to produce the most realistic effect can be easily determined by experiment.

A circular disc of metal a trifle larger than the lamp, should be fastened to the tip of the lamp with sealing-wax, or any soft, water-resisting cement; this cuts off the direct light of the lamp

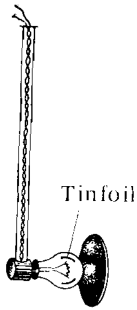


Fig. 107

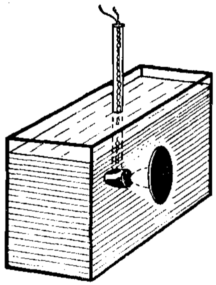


Fig. 108

and represents the dark disc of the moon. The whole is to be immersed in the tank with the lamp in a horizontal position and the metal disc close against the front glass plate (Fig. 108). It is a good plan to have a rheostat in circuit with the lamp to regulate the intensity of the illumination. On turning on the current and seating ourselves in front of the tank, we shall see a most beautiful corona, caused by the scattering of the light of the lamp by the small particles of mastic suspended in the water. If we look at it through a Nicol prism we shall find that it is radially polarized, a dark area appearing on each side of the lamp, which turns as we turn the

Nicol. The illumination is not uniform around the lamp, owing to unsymmetrical distribution of the candle-power, and this heightens the effect. If the polar streamers are found to be too sharply defined or too wide, the defect can be easily remedied by altering the tinfoil strips.

The eclipse is not yet perfect, however, the

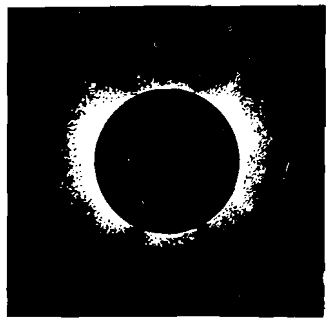


Fig. 109

illumination of the sky background being too white and too brilliant in comparison. By adding a solution of some bluish-green aniline dye (I used malachite-green), the sky can be given its weird colour and the corona brought out much more distinctly. If the proper amount of the dye be added, the sky can be strongly coloured without apparently changing the colour of the corona in the slightest degree, a rather surprising circumstance since both are produced by the same means.

We should have now a most beautiful and perfect reproduction of the wonderful atmosphere around the sun, a corona of pure golden white light, with pearly lustre and exquisite texture, the misty streamers stretching out until lost on the bluish-green background of the sky. The rifts or darker areas due to the unequal illumination are present as well as the polar streamers. The effect is heightened if the eyes are partially closed.

A photograph of one of this artificial eclipses is reproduced in Fig. 109. Much of the fine detail present in the negative is lost in the print.

Believe It or Not

by G. Kosourov

Vision is our main source of information about the environment, and we are used to trusting our eyes. The expression 'I can't believe my eyes', for example, indicates extreme surprise, and normally, our reliance on our eyes is justified. The eyes, with the appropriate parts of the brain, are a sophisticated analytical apparatus which serves our purposes under diverse conditions—in a bright sunlight, or darkness, with slow or rapid movements. The image that reaches the retina appears free of defects. The image seems quite sharp, and the perspective is correct. Straight lines seem straight. Objects lack iridescence, i.e., chromatic aberration.

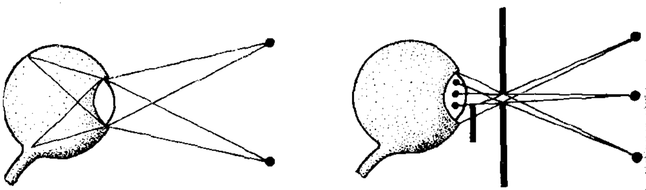
Our eyes are not ideal instruments, however. Objective studies show that the eye possesses all the drawbacks of a lens. Our brain, however, constructs a correct image from the incorrect picture of the environment on the retina of the eye. For example, a man, who develops short-sightedness gets a very distorted perspective

when he puts on glasses for the first time in his life. Straight lines seem curved; planes are irregular and sloping. Sometimes this causes slight giddiness. But as time passes, the man begins to perceive perspective and straight lines correctly. The world again appears undistorted, even though its picture on the retina remains askew.

Under unusual conditions—when the eyes get conflicting information, when contrasts are great, when correct perception of distances, dimensions, and ratios is difficult, or when certain parts of the retina are tired from constant stimulation—our brain falters, and various optical illusions can occur. We shall give you some illustrations of how our eyes can be mistaken. We do not want to undermine your trust in your eyes but to show you the importance of the synthesis performed by the brain in forming images.

For the first experiment, which is usually used as proof that the image on the retina, like that on a camera, is upside down, we need two pieces of cardboard. Two postcards, for example, will do. Make an opening about 0.5 mm in diameter in one of the cards with a large needle, and hold it about 2-3 cm from your eye. Look through the hole at a bright landscape, sky, or lamp. Now gradually shade the pupil by slowly moving the edge of the second postcard upwards. The shadow of the edge of the postcard will appear to move downwards from above into the field of vision.

Let us discuss the optical outlay of the experiment in more detail. As long as the postcard with the opening is not held in front of the eye, all points in the field of vision send their rays over the entire surface of the pupil into the eye (*Fig. 110a*). And the light from every point of the pupil is distributed over the entire surface of the retina. When we place the first postcard in front of the eye, every point in the field of vision is represented by rays passing through a small portion of the pupil (Fig. 110*b*). The upper points are transmitted by rays passing



(*a*) (*b*)

Fig. 110

through the lower part of the pupil, whereas lower points are transmitted by rays passing through the upper portion of the pupil. By shadowing the lower portion of the pupil with the edge of the postcard, we block the upper field of vision, and we see the edge of the card descending from above. This unusual experiment is obviously not dependent on the path rays take to the eye and, therefore, cannot be used as proof that the image in the retina is upturned. The field of vision is formed before the light rays enter the pupil. This can easily be proved if the image is projected onto a mat glass plate instead of the human eye.

Our second experiment will show how the eyes handle conflicting information. Place a paper tube about 2 cm in diameter over one eye, and

look through it at objects in front of you. Now hold the palm of your hand in front of your other eye about 10-15 cm away from your face and close to the tube. You will clearly see a hole in the palm, through which objects can be seen. The image of the centre of the palm is completely suppressed by the images seen through the tube.

A more refined experiment can be performed with the different information the right and left eyes receive. Tie a small white object to a white thread. Now start this pendulum swinging in one plane, and then step back 2-3 m. Hold a light filter of any density and colour in front of one eye, and watch the pendulum. You will see that it is not swinging in one plane but making an ellipse. If you move the light filter in front of the other eye, the motion of the pendulum will reverse.

The optical illusion in Fig. 111*a* is well known: the straight line seems to break when it intersects the black strip. Not many people know, however, that if the figure is completed by drawing a winch and a load (*Fig. 111b*), prompting the brain to believe that the line is a taut winch line, the illusion of a broken line disappears.

Our last experiment shows how an image is formed when the brain is given a choice of alternatives. Figure 112 shows two pictures of the lunar landscape in the area of the Mare Humorum and Apennine Ridge. In one of the pictures you see circular lunar mountains and in the other circular lunar craters, i.e., an inverse landscape. Turn the pictures, and the landscape will reverse. These pictures are absolutely identical, but one of them is upside down. The effect of inverse relief is often observed when the Moon is viewed through a telescope. The astronauts who visited the Moon had difficulty correctly perceiving the landscape which lacked atmospheric perspective in the highly contrastive surroundings. The effects of reverse motion can be observed by

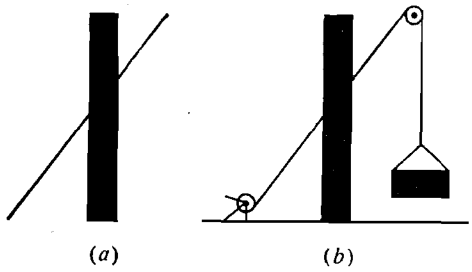


Fig. 111

watching the silhouette of a dish-shaped radar aerial as it rotates. You will notice that the aerial bluntly reverses the direction of its rotation at certain moments. Students used to be advised to study this phenomenon by observing the silhouette of a windmill.

Many interesting illusions are related to colour perception. Optical illusions are not simply amusing tricks, since studies of the organs of sight under unusual conditions can help explain the complex processes in the eye and brain during the synthesis of images of the environment. Readers who wish to learn more about physiological optics are referred to *Experiments in Visual Science* by J. Gregg.* The book contains a

* Gregg James R. *Experiments in Visual Science. For Home and School.* New York. Ronald, 1966, 158 p.

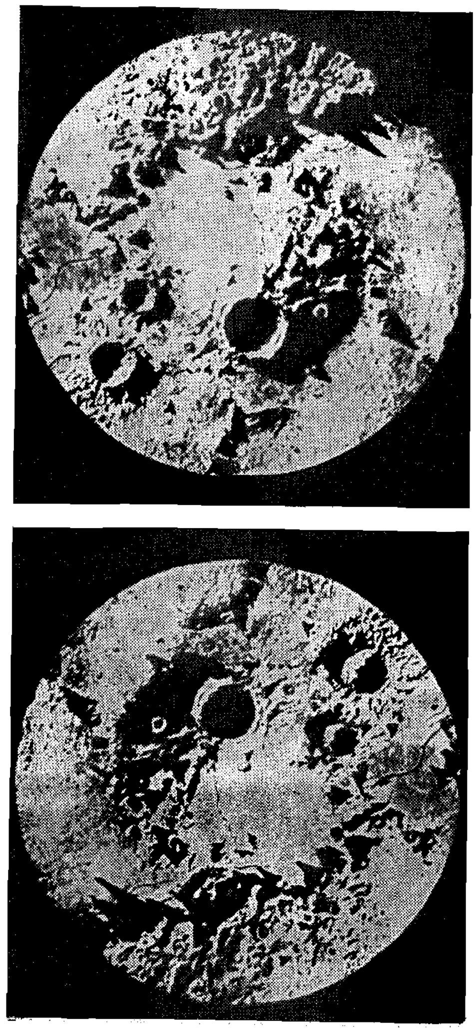


Fig. 112

number of simple experiments with visual perception. All of them are quite manageable by school children, and many are particularly instructive. Unfortunately, the language used to describe physical optics is far from scientific.

Colour Shadows

by B. Kogan

A Green Shadow

In a room lit by normal white light, turn on a desk lamp with a red bulb. Place a sheet of white paper on the desk and then hold a small object, a pencil, for example, between the lamp and the desk. The paper will cast a shadow, which will not be black or grey but *green*. This effect seems to relate more to physiology and psychology than to physics. The shadow of the object appears green because it contrasts with the background, which, although actually reddish, we perceive as white since we know the paper is white. The absence of the colour red in the area covered by the shadow is apparently interpreted by our brain as the colour green. But why green?

Red and green are *complementary* colours, i.e., when combined, they produce white. What does this mean? As early as the seventeenth century, Newton found that white sunlight is complex and combines the primary colours violet, blue, green-blue, green, yellow, orange, and red. This can be illustrated with a glass prism. If a narrow beam of sunlight is passed through the prism, a *coloured image* of the beam will appear. Newton

also used a lens to combine all these colours and obtain the colour white again. It was found that when one of the colours, green, for example, is 'intercepted', the beam becomes coloured, in this case, red. When yellow is intercepted, the beam becomes blue, and so on. Thus, green and red, yellow and blue, and similar pairs of colours are complementary.

This interesting experiment can also be carried out with light bulbs of other colours. If the light bulb is green, for example, the shadow will be red. If the bulb is blue, the shadow will be yellow, and if the bulb is yellow, the shadow will be blue. Generally, the colour of the shadow will always be complementary to the colour of the bulb. The above phenomenon can easily be observed in winter time near neon advertisements in the city. Shadows from the neon, which are complementary to the colours of the advertisement itself, should show up clearly when the ground is covered with snow.

Red Leaves

Turn off the light in your room, and switch on a lamp with a blue bulb. Look at the leaves of plants in the room: the green leaves look *red*, rather than green or blue, in the blue light. What causes this? Actually, the glass of the blue light bulb passes a certain amount of red light along with the blue. At the same time, plant leaves reflect not only green but red light to some extent as well, while absorbing other colours. Therefore, when the leaves are illuminated with blue light, they reflect *only red* and, therefore, appear as such in our eyes. This same effect can be obtained in a different way by looking at the leaves through blue spectacles or a blue light filter. The famous Soviet scientist K. Timiryazev was speaking about such eye-glasses when he wrote: "You have only to put them on, and the whole world looks rosy for you. Under a clear blue sky a fantastic landscape of coral-red meadows and forests rolls out ..."

What Colour is Brilliant Green?

by E. Pal'chikov

What colour is the 'brilliant green' often used as an antiseptic for minor bruises and wounds? Many would probably answer that it is green (and they would be right). But look through a bottle of the brilliant green at a bright light source, the sun, the filament in an electric bulb, or an arc discharge, for example. You will see that the brilliant green transmits only the colour red. So, is the 'green' tincture red?

Pour a brilliant green solution* into several developing trays of various depth or thin-wall glass beaker, and examine it in the light. Thin layers of the solution are, indeed, green, but thicker layers have a grayish tint (with purple hues), whereas the thickest layers appear reddish. In other words, the colour depends on the thickness of the layer of solution. How this can be explained? Two transparency bands—a broad

* The tincture is not diluted, the vessels must be extremely shallow.

blue-green band and a narrow red band (Fig. 113)—are visible in the transmission band of a thin layer of brilliant green. In reality, however, the red band is not narrow: it extends into the infrared range, although the human eye can detect only a small fraction of the band. The absorption

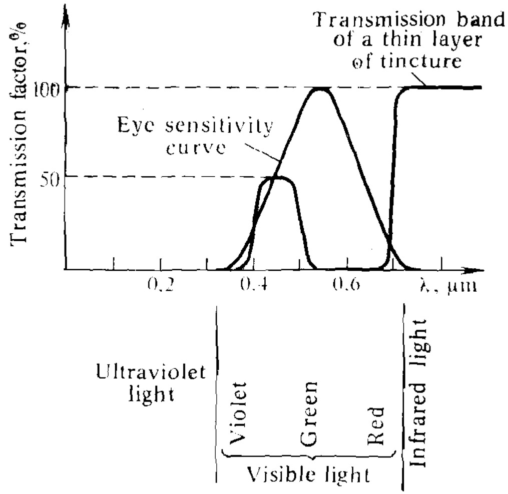


Fig. 113

in the red band is lower than that in the blue-green band (the transmission factor for the red band is substantially greater than that for the blue-green). But the blue-green band is wider than the red, and it is situated in the part of the spectrum where the eye is most sensitive. Therefore, a solution of brilliant green in a thin layer will appear green.

Now let us double the thickness of the layer or place two layers over one another, which will have the same effect. Obviously, the transmission factor will decrease. To get the value of this new transmission, we multiply the factors of the first and second layers. In other words, the transmission factor for the total layer should be squared. In this case, the transmission factor for the blue-green band will decrease very significantly, whereas it will remain almost the same for the red band.

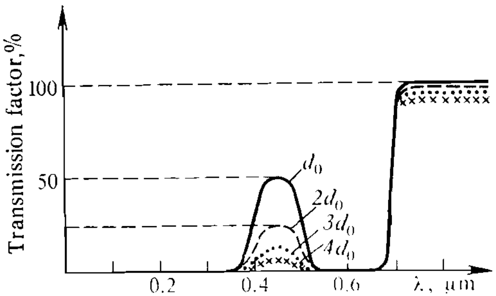


Fig. 114

Figure 114 shows changes in the transmission factors for the blue-green and red bands with increases in the thickness of the brilliant green. The proportion of blue-green to red obviously decreases. At a certain thickness, the solution will transmit only red light. Now answer the question again. What is the real colour of brilliant green?

An Orange Sky

by G. Kosourov

A number of interesting experiments concern colour perception. Those we suggest here involve various optical illusions caused by unusual visual conditions or eye fatigue.

Colour perception is a very complex mechanism, which has not yet been studied adequately. The retina of the eye contains two types of colour-sensitive cells called rods and cones. The rods contain photochemically sensitive pigment, i.e., purpura or rhodopsin. When acted upon by light, rhodopsin decolourizes and reacts with the nerve fibres, which transmit signals to the brain. In very bright light, the pigment decolourizes completely, and the rods are blinded. The process is reversed in the dark, i.e., purpura is recovered. Rod or twilight vision is very sensitive but achromatic, since the rods cannot distinguish colours. In fairly bright light, cone vision, which is sensitive to colour, takes over. Many convincing experiments indicate that the cones contain three kinds of photochemically sensitive pigments which are maximally sensitive in the red, green, and blue bands of the spectrum. The variable degree of their decolourization produces the sensation of colour in the brain and allows us to see the world in different colours, tints, halftones, and hues. This principle of trichromatic vision is used in motion pictures, colour television, photography, and printing. Methods for measuring colours quantitatively are also based on the trichromatic principle.

Colour perception can be generated not only by colour itself but by intermittent illumination, for example. To test this, draw the black-and-white circles shown in Fig. 115*a-d* with India ink. Your circles should be approximately 8-12 cm in diameter. Cut out the discs, and spin them slowly, e.g., 1-3 revolutions per second, on the axis of a film projector, record player, tape recorder, or a child's top. Instead of black arcs you will see coloured circles. The colour

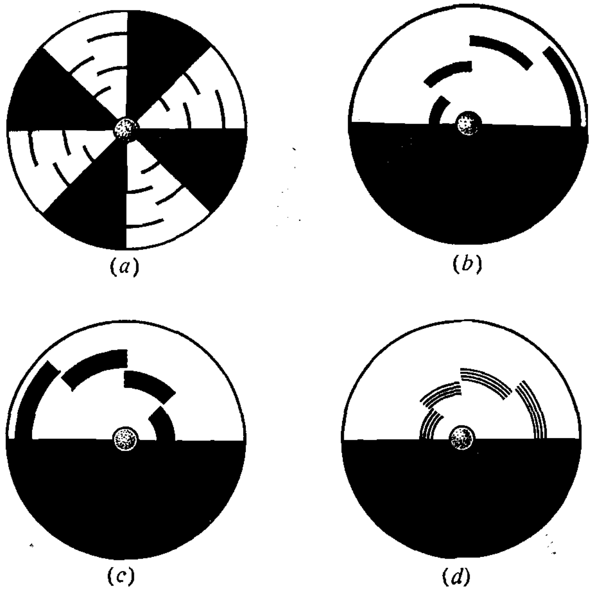


Fig. 115

depends on the velocity of the revolutions, the illumination, and the design on the circle itself. On the disc in Fig. 115*a*, for example, the arcs that follow the black sectors (in the direction of rotation) appear red when poorly lighted, and yellow under dazzling light. At a certain speed and brightness, the black sectors appear blue.

This phenomenon is still incompletely understood.

Colours are distinguished not only by shade or variety but also by saturation. If we slowly add white paint to red, the red will gradually become pinker. In paintings and, particularly, in printed copies of paintings, it is very difficult to obtain well saturated tones and a broad spectrum of brightness. The brightness ratio of the brightest white paint to the deepest black barely reaches one hundred, whereas in nature the ratios reach many thousands. Reproductions of paintings, therefore, often appear either washed out or too dark, and one of the most important elements of steric perception—atmospheric perspective—is, thus, lost. The image of a landscape or a genre scene in such paintings seem two-dimensional. The range of brightness in projections of slides onto a screen is much broader. That is why photographs on colour reversible film are so expressive and have such wonderful perspective.

The perception of a painting can be improved considerably by illuminating it in a special way. Make a negative from a colour picture out of a magazine and then use a contact printing process to make a black-and-white slide of the negative. Now project the slide onto the original using a projector with a powerful light source. Make sure that the projected slide lines up exactly with the original. The result will make you glad you made the effort. The picture will seem livelier; it will seem to gain dimension and a special charm. Now turn off the projector, and you will see how dull and inexpressive the original is with uniform lighting.

The following experiments deal with so-called successive colour images. Complete recovery of colour-sensitive pigment is a rather slow process. If you look at a monochromatic picture for a long time and then shift your eyes to a piece of white paper or a white wall or ceiling, the white will appear to lack the colour that has tired the eyes. The same picture will appear on the white surface but it will be in the complementary colour. Cut out red, orange, yellow, green, blue, and violet paper squares 2 by 2 cm in size. Put one of these coloured squares on a piece of white paper in front of you and look at it, without straining your eyes, for about 30 seconds. Stare fixedly at one point, and do not let the image shift on the retina. Now shift your gaze to a field of white, and after a second you will see a clear afterimage of the square in a complementary colour. This shows that the complementary to red is green, to blue—orange, and to yellow—violet. Each pair of complementaries, if mixed, should produce achromatic white or grey.

To mix complementaries place two 'complementary' squares (red and green, for example) close together, and put a glass plate between them upright (Fig. 116). Now position your eye so that one of the squares is visible through the glass and the other reflected in it. By varying the angle of the plate and thus changing the ratio of the light fluxes from the squares, you can almost completely decolourize the superimposed images. To achieve complete achromatization of the image, the colours must match perfectly. A dull brown colour is most often obtained. But if the colours are absolutely uncomplementary, green

and yellow or red and violet, for example, the resulting colour will always be bright. The images appear even brighter if the squares are placed against a complementary, rather than white background.

The most striking and inexplicable colour illusion is illustrated by our last experiment. We know that colour reproduction is based on

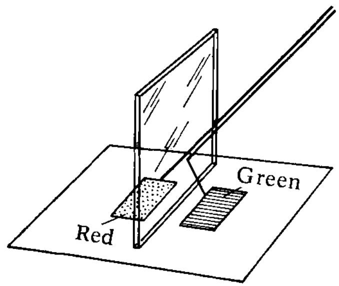


Fig. 116

the principle of trichromatism. If we photograph the same scene three times using three different light filters—red, green, and blue—and then project the pictures from three different projectors onto the same screen, the resulting picture will have realistic colours. The light filters should produce the colour white when combined. Try this experiment with only two complementary light filters, red and green, for example. The transmission of colour should be good in this case too, although not as perfect as in the three-colour projection. Experiments show that even one filter is enough for projection.

Photograph the same scene twice on panchromatic film without moving the camera. Use a red light filter for the first picture and a green filter for the second. The filters from a school kit will suit this purpose since they need not be carefully matched. Use a contact printing technique to make positives, and then project the two slides

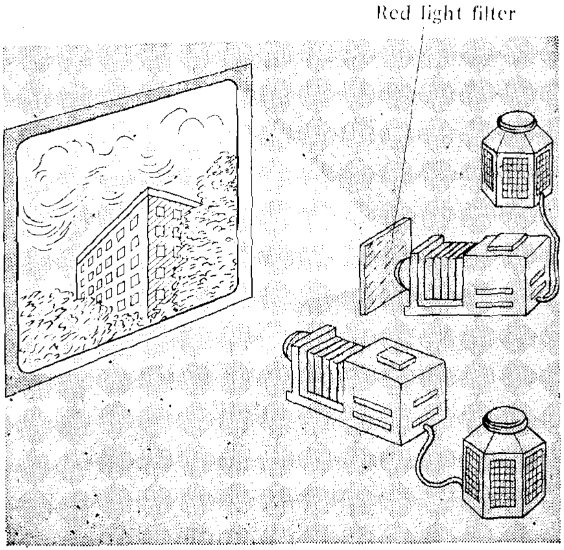


Fig. 117

from two projectors onto a single screen. Line the images up exactly. Now place a red filter in front of the projector with the slide taken with a red filter. Leave the picture in the second projector black and white (Fig. 117). The result will be a *colour* picture full of tones and hues even though you are projecting only red and black and white pictures in which the distribution of

light and shade differs. Objective investigations of the light reflected from the various places on the screen show only the colour red, although with different degrees of clarity and saturation. Colour perception in this particular case is entirely subjective. The projectors should be powered by separate autotransformers so that the illumination from each can be controlled independently. Normally, the colour seems natural when the screen is dimly lit.

Thus, phenomena that seem simple and obvious are actually full of secrets and mystery.

The Green Red Lamp

by V. Mayer

In his excellent book *The Universe of Light*, W. Bragg describes an elegant experiment to demonstrate a peculiar property of the human eye. The experiment is simple enough to be reproduced at home without much difficulty. The necessary equipment can be assembled from a toy constructor kit (Fig. 118). Attach a micromotor (*2*) by an aluminium or tinplate mount to an aluminium baseplate (*1*) 15 × 60 × 110 mm in size. Insert a shaft (*4*) with a pulley (*5*) whose inner diameter is 15-25 mm into the openings of two risers (*3*) about 60 mm in height.

Attach a cardboard disc (*6*) 100-140 mm in diameter to one end of the shaft before installing (if the shaft is threaded, the disc can be

* *The Universe of Light*. By Sir William Bragg, London, Dover, 1959.

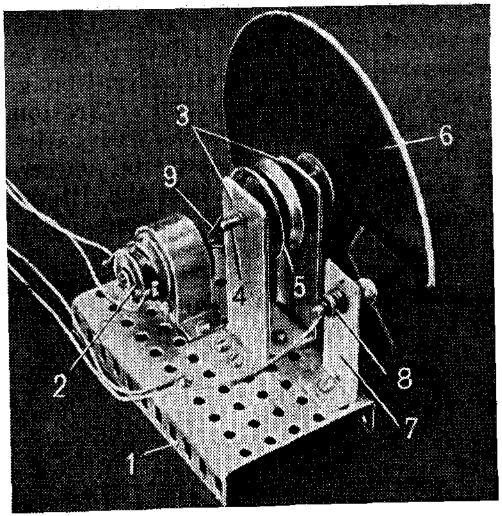


Fig. 118

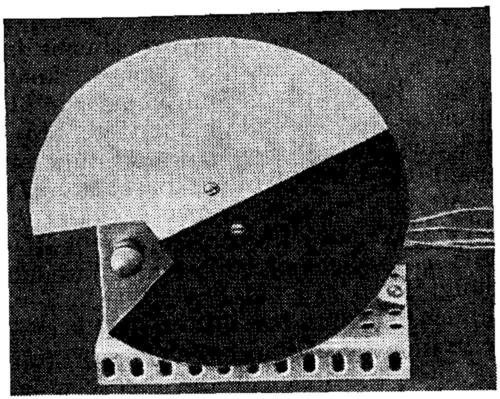


Fig. 119

fastened with nuts). Fix another riser (*7*) to the same base plate with an opening for a small light bulb (*8*). Connect the shaft of the micromotor and the pulley with a rubber ring (*9*). The motor should be connected to one or two flashlight batteries connected in series. According to Bragg, the disc should rotate at a speed of 2 or 3 revolutions per second. The speed can be controlled to a certain extent by slowing the pulley with one finger.

Test the setup before beginning the experiment. Then cut a sector in the cardboard disc whose arc is about 45°. Glue white paper to one half of the remaining sector and black paper to the other half (Fig. 119). Paint the bulb of the flashlight, which should be rated for 3.5 V, with red nitrocellulose enamel (fingernail polish will do). When the enamel has dried, insert the light bulb into the opening in the riser, and supply it with wires to the batteries. Place a desk lamp 20-50 cm in front of the disc to illuminate it squarely. Now connect the bulb to the batteries, and switch on the motor.

If the disc rotates so that on each revolution the bulb is first shaded by the black sector, the bulb will appear red regardless of the strength of illumination or rotation speed. If we change directions by changing the polarity of the batteries so that the bulb is shaded first by the white sector, the bulb will appear green or blue-green! If the conditions of the experiment (the speed of rotation or the colour of the enamel) have not been carefully fulfilled, the lamp will appear light blue with a whitish tinge rather than blue-green.

Now let us try to explain the results of the experiment. The disk spins rapidly, and each time the red bulb is revealed through the cut-out sector, a brief red image reaches the retina of the eye. If the white sector shades the bulb as the rotation continues, the retina receives a reflection of the scattered white light from the desk lamp. This white light acts on the retina for a longer time than the red. After the black sector passess before the eye, the process starts again, and the lamp appears blue-green since the eye perceives the colour complementary to the red bulb.

The retina apparently becomes more sensitive to the other spectral components of white after brief illumination with red light. When the eye, which 'tires' of the colour red, is illuminated by white light, it perceives the white without a 'red component'. The retina has become more sensitive to the colour complementary to red—blue-green. Since the retina is exposed to the white light much longer than to the red, the light bulb appears blue-green rather than red. This hypothesis is supported by the result of rotation in the opposite direction so when the bulb is shaded first by the black sector. During exposure to the colour black the part of the retina on which the red image of the bulb appears is able to recover. Therefore, when the white half of the disc appears, the eye perceives all the colours that compose white equally. Since the red light acts on the retina for a longer time than all other components (first the red component of the white colour appears and then the red colour of the bulb itself), the bulb looks red.

Measuring Light Wavelength with a Wire

by N. Rostovtsev

Stretch a thin wire (*W*) 0.05-0.12 mm in diametre vertically about 2-3 mm in front of an imaginary eye (*E*). Now direct a beam of light from a point source towards the eye (Fig. 120). To the right and left of the point source, we will

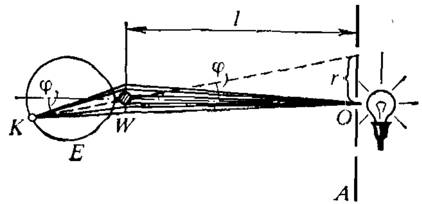


Fig. 120

see a bright thin band. The band, which appears as a result of the diffraction of light is called a diffraction fringe. We will use an ordinary light bulb or a bulb from a flashlight as a light source in our observations. Place the light behind a small opening (*O*) in a screen (*A*) 1-1.5 m away from the observation point. The wire (*W*) can be replaced with a thin filament or hair.

If we examine the centre of the diffraction fringe carefully, we can detect a white band with reddish edges. This band is called the central maximum. It is bounded on either side by darker bands, which are called first minima. Colour bands follow next, which, as we move from the centre to the edges, change gradually from greenish-blue to red. Darker bands, called second minima, reappear at the edge of the red. This pattern then repeats, although the minima become paler, and the light bands finally merge into a continuous band. Observations with wires of different diametres show that the smaller the wire diametre, the greater the distance between adjacent minima.

To perform interesting experiment place the wire used for diffraction observations between the jaws of a vernier caliper. Tighten the caliper slightly, and then carefully remove the wire. The width of the slit between the jaws will equal the diametre of the wire exactly. Now look through this slit from the same distance from which you made your diffraction observations, and align the slit with the light source O. On either side of the source, you should see a diffraction fringe whose minima and maxima are exactly the same distance apart as those in the diffraction of the wire. This observation is an excellent illustration of the Babinet principle, according to which diffraction patterns from a screen and an opening of the same width are identical outside the area of a direct ray.

Now coil the piece of wire we have been using for our observations of the diffraction fringe into a disc whose diametre is about half the diametre of a dime. For this we will need a wire 2-3 m long. Hold this disc in front of one eye, and look at a point source. You should see a number of haloes: a central white circle with reddish fringe, surrounded by coloured circles. The haloes are separated from one another by narrow dark circles, i.e. the minima. Each such minimum

follows the red fringe of the preceding halo. If the observation is made from the same distance as in the experiment with the diffraction of the wire, the diametres of the dark circles will equal the distances between the respective minima of the diffraction fringe. The finer the diametre of the wire, the more visible the haloes will be.

Why do such haloes appear if a coil of wire is placed in the path of rays from a point source? Each small section of the wire in front of the eye produces its own diffraction fringe, which is symmetrical with respect to the light source. Since every section in the coil is oriented differently, the resulting diffraction fringes are tilted differently around a single point, which coincides with the light source. Since the thickness of the wire is uniform, minima of the same order are located the same distance from the light source in all diffraction fringes and merge to produce dark circles. The coloured sections between the minima also merge to produce coloured circles.

Now let us determine the conditions in which minima appear in the diffraction pattern produced by a wire with d diametre and a slit of the same width. Since the distance between the minima is the same in both cases, either the wire or the slit can be analysed. To simplify the calculation, we shall select the slit. Let us examine the waves that do not change direction after passing through the slit (in Fig. 121 they are represented by dotted lines). The eye converges them on the retina at point O. Waves from all points of the slit enhance each other at this spot because they reach the eye regardless of the distance travelled, and at point O they are in the same phase. Therefore, the central maximum is formed in the neighbourhood of the point O.

The eye converges waves diffracted at angle φ to the initial direction at point K, where the waves interfere as a result of superposition. The result of the interference will depend on the difference in the distance travelled by the rays emanating from the extreme points A and B of

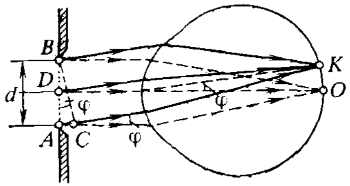


Fig. 121

the slit. Draw a section BC perpendicular to the ray emanating from point A. The new intercept AC equals the difference between the distances travelled by the two extreme rays. It follows from Fig. 121 that $AC = d \sin \varphi$, where d is the slit width.

Calculations show that in the diffraction pattern produced by a rectangular slit, minima are observed when the difference in the distance travelled by the waves emanating from the extreme points of the slit is

$$d \sin \varphi = k\lambda \qquad (1)$$

where λ is the light wavelength and k is the number (order) of a minimum ($k = 1, 2, 3, \ldots$).

Now we shall test the validity of formula (1) for the first minimum, i.e. $k = 1$. Let the second-

ary waves that emanate from all points of the slit travel at an angle φ so that

$$d \sin \varphi = \lambda \qquad (2)$$

Divide the slit into two imaginary rectangular strips (zones) AD and DB, both of width $d/2$. According to definition (2) the difference in the distance travelled by rays from points A and D is $\lambda/2$. The difference between rays from any two points $d/2$ apart on the slit will be the same. The waves that travel $\lambda/2$ suppress one another by superposition and, therefore, if condition (2) is observed, the waves from zone AD will suppress the waves from DB. As a result the first minimum will appear at point K.

Similarly, we can show that the next (second) minimum will appear if $d \sin \varphi = 2\lambda$. In this case, the slit should be divided equally into four zones. The difference in travel for the waves both from the first and second, and from the third and fourth zones will be $\lambda/2$. Therefore, the wave from the first zone will suppress that of the second, and the wave of the third zone will suppress that of the fourth. The second minimum appears on the retina where these waves are superimposed.

According to formula (1), the light wavelength can be determined from the formula

$$\lambda = \frac{d \sin \varphi}{k} \qquad (3)$$

Measurements of λ can be simplified considerably by using a primitive metre called an eriometre. You can make an eriometre from a square piece of cardboard whose sides are 10-15 cm long.

Draw a circle with a radius of 20-30 mm in the middle of the square. Make an opening of 2-3 mm in diametre in the centre and 6-8 openings of smaller diametre around the circumference.

Place the eriometre A directly in front of an electric bulb. Now stand 1-2 m away from the instrument so that rays pass directly from a sector of the incandescent filament through opening O to the eye. Hold a coil of wire in front of one eye, and move it perpendicular to the rays until the haloes are clearly visible. Vary the distance between the instrument and your eye to find a position from which the perforated circumference of the eriometre coincides with the middle of dark ring of k order (in Fig. 120, $k = 2$).

As is obvious from the figure, the tangent of the diffraction angle φ for a dark ring is calculated from $\tan \varphi = r/l$, where r is the radius of the circumference of the eriometre and l is the distance from the instrument to the coil of wire. At low diffraction angles, which are common in such measurements, the following relationship is true

$$\sin \varphi \approx \tan \varphi = \frac{r}{l}$$

By substituting the value of $\sin \varphi$ in expression (1), we get a formula for wavelength

$$\lambda = \frac{rd}{kl} \qquad (4)$$

We already know the radius of the eriometre r. The distance l can be easily measured. The order of a dark ring k is determined by observing the haloes. The wire diametre d is measured with a

micrometre. If the measurements are taken in white light, we can determine the effective light wavelength to which the human eye is most sensitive with formula (4). This wave is approximately 0.56 μm long, and waves of this length correspond to the green section of the colour spectrum.

Haloes may appear in diffraction patterns caused by round obstacles. They can be observed by spreading a small amount of lycopodium powder (composed of the spores of a club moss, it can be obtained in any drugstore) on a glass plate. Gently tap the edge of the plate against your desk to remove excess powder. Now, look through the plate at a light source. You should see haloes formed by the round spores, which act as obstacles. Especially bright haloes appear around a drop of blood pressed between two glass plates. In this case the diffraction is caused by red blood cells called erythrocytes.

The haloes produced by round and rectangular obstacles differ slightly. The minimum condition for haloes from rectangular obstacles is described by formula (1). The minimum condition for haloes from round obstacles is

$$d \sin \varphi = 1.22\lambda;\ 2.23\lambda;\ \ldots \qquad (5)$$

Here d is the diametre of a round screen. With the help of an eriometre and formula (5), we can determine the average diametre of club moss spores and erythrocytes without a microscope!

Haloes can be observed around the Sun, the Moon, and even other planets. These haloes appear when light passes through clusters of water drops or ice crystals suspended in the atmosphere (through a thin cloud, for example). Clear haloes appear only if the cloud is made of drops of equal diametre or crystals of the same thickness. If the drops or crystals vary in size, however, rings of different colours superimpose to produce a whitish corona. This is why a halo appears around the Moon, particularly at twilight on a clear day. The water vapour in the atmosphere condenses slightly on such nights and produces small drops or crystals of the same size. Haloes sometimes occur when the light from a distant lamp passes through a fog or a window pane covered with a thin layer of ice crystals or condensed vapour.

EXERCISES

1. The effective light wavelength is approximately 0.56 μm. Using an eriometre, determine the diametre of the strands in nylon stockings and ribbons.
2. How does the appearance of the halo indicate whether the cloud contains water droplets or ice crystals?
3. The angular diametre of the Moon is 32 minutes. Determine the diametre of the drops in a cloud, if the angular radius of the central circle of its halo is four times the angular diametre of the Moon.

Measuring Light with a Phonograph Record

by A. Bondar

One of the most accurate ways of determining the spectral composition of radiation is the method based on diffraction. A diffraction grating is a good spectral instrument. We can observe

diffraction and even measure the wavelength of visible light with a standard phonograph record. In acoustic recording evenly spaced grooves are cut on the surface of a disk. These grooves scatter light, whereas the intervals between them reflect it. In this way the disk becomes a reflecting diffraction grating. If the width of reflecting strips is a and the width of scattering strips is b, then the value $d = a + b$ is the period of the grating.

Consider a plane monochromatic wave of length λ which is incident at angle θ to a grating with period d. According to the Huygen-Fresnel principle, every point of a reflecting surface becomes an individual point source sending out light in all possible directions. Consider the waves travelling at an angle φ to the grating (see Fig. 122). These waves can be collected at one point with a condensing lens (the crystalline lens of the eye, for example). Let us determine under what combination of conditions the waves will enhance one another.

The difference between distances travelled by rays *1* and *2* issued by points A and B from neighbouring reflecting areas (Fig. 123) is

$$|AK| = |NB| = d \sin\varphi - d \sin\theta = d(\sin\varphi - \sin\theta)$$

(KB is the front of the reflected wave directed at angle φ, AN is the front of the incident wave). If the difference is a common multiple of the wavelength, the phases of oscillations travelling from points A and B will be equivalent and will enhance each other. All other reflecting areas of the grating behave similarly. Therefore, the condition of central maximum is described as

$$d\,(\sin\varphi - \sin\theta) = k\lambda \qquad (1)$$

where $k = 0, 1, 2, \ldots$. Hence we can determine the wavelength λ. For this we need to know the grating period d, the incidence angle θ for the wave with respect to the grating, and the angle

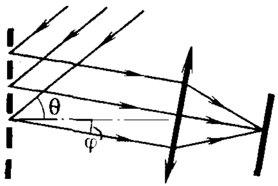


Fig. 122

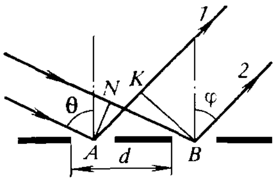


Fig. 123

of its direction to a corresponding maximum φ. Normally, *the grating period is much larger than* the wavelength (d is much larger than λ), and angles φ are, therefore, small. This means that the central maxima are situated very close to one another, and the diffraction pattern is rather hazy. The larger the incidence angle (θ), however, the larger the φ angles and, consequently, the more convenient the measurements. Thus, the rays should be directed towards the grating at an angle.

So far we have been discussing monochromatic light. What if complex white light strikes such a grating? It is clear from equation (1) that the location of every central maximum depends on wavelength. The shorter the wavelength, the smaller the angle φ corresponding to the maximum. Thus, all *maxima* (except for the central) stretch out in a spectrum whose violet end is directed towards the centre of the diffraction pattern and whose red end is directed outward. Two spectra of the first order, followed by two spectra of the second order, and so on lie on either side of the central (zero) maximum. The distance between corresponding lines of spectra increases with an increase in the order of the spectrum. As a result, spectra may overlap. In the spectrum of the Sun, for example, second- and third-order spectra overlap partially.

Now let us turn to the experiment itself. To measure the wavelength of a specific colour, we need to determine the period of grating (d), the sine of the incidence angle of the ray with respect to the grating ($\sin\theta$), and the sine of the angle that determines the direction towards a maximum, for example, the maximum of the first order ($\sin\varphi_1$). The period of the lattice can easily be determined by playing the record:

$$d = \frac{\Delta R}{n\Delta t}$$

Here ΔR is the absolute displacement of the stylus along the radius of the record in Δt time, and n is the number of revolutions per unit of time. Usually, d is approximately 0.01 cm.

A desk lamp can be used as a light source. Make a screen with a slit out of cardboard, and cover the lamp to avoid light interference in diffraction pattern analysis. The filament of the bulb should be visible through the slit. Place the lamp close to one wall of the room. Place the record horizontally near the opposite wall. Now find the image of the slit (see Fig. 124). You should see the diffused colour bands that indicate the spectrum of the first order ($k = 1$) simultaneously. It is easy to prove that the greater the angle θ, the wider the colour image of the slit and the more accurate measurements of the angle at which the ray in question is diffracted will be.

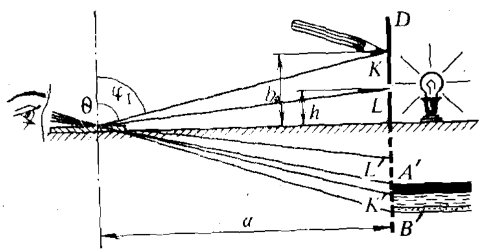


Fig. 124

To determine $\sin \varphi_1$, have a friend hold a pencil (or some other object) over the slit so that its image coincides with the selected spectrum band in the light reflected from the grating (as from a flat mirror) (see Fig. 124). Once we have measured a, b, and h with a ruler, we can determine $\sin \varphi_1$ and $\sin \theta$

$$\sin \varphi_1 = \frac{a}{\sqrt{a^2+b^2}}$$

$$\sin \theta = \frac{a}{\sqrt{a^2+h^2}}$$

These expressions could be somewhat simplified. Since $b \ll a$, and $h \ll a$, then

$$\frac{a}{\sqrt{a^2+b^2}} = \frac{1}{\sqrt{1+b^2/a^2}} \approx 1 - \frac{1}{2}\frac{b^2}{a^2}$$

and

$$\frac{a}{\sqrt{a^2+h^2}} = \frac{1}{\sqrt{1+h^2/a^2}} \approx 1 - \frac{1}{2}\frac{h^2}{a^2}$$

And finally

$$\lambda = d(\sin \varphi_1 - \sin \theta) \approx d\,\frac{h^2-b^2}{2a^2}$$

It is interesting to compare the estimated wavelengths of various colours with the values in the reference tables. In our experiments the error, with very careful measurements, was on the order of 10^{-8} m. This level of accuracy is quite acceptable for wavelength in the visible band (λ is approximately 10^{-7} m).

A Ball for a Lens

by G. Kosourov

Geometrical optics is based on the idea that light rays move in straight lines. You can prove this for yourself experimentally. Replace the objective lens of your camera with a sheet of black paper with a very small opening in it. Brightly illuminated objects can be photographed with such a device, called a camera obscura. The picture in Fig. 125, for example, was taken with an ordinary camera whose objective lens was replaced with a sheet of black paper in which an opening 0.22 mm in diametre had been made. The ASA 80 film was exposed for 5 seconds. The image on the film coincides exactly with the central projection of the points of the object by straight lines passing through the opening. The image is a hard evidence that light rays travel in straight lines.

A shadow on a white screen cast by an opaque object is explained as a projection of the contour of the object on the plane of the screen by rays

Fig. 125

from every point of the light source. Since the light source is usually rather large, the dark centre of the shadow called the umbra is bounded by a diffused semishadow or penumbra. We might expect to reduce or even eliminate the penumbra by reducing the size of the light source. Experiments show quite the opposite, however. When the light source is fairly small, it reveals phenomena that were earlier masked by the penumbra. For example, the straight edge

of an opaque plate casts the shadow shown in Fig. 126. The shadow was photographed at a distance of 0.5 m from the screen in white light through a red filter, and the picture was then enlarged. The distance between the first two dark bands is 0.6 mm. The edge of the shadow is diffused, and dark and bright bands of diminishing contrast lie parallel to the edge. If the light source is white, the bands are all the colours of the spectrum.

A shadow cast by a thin wire (Fig. 127) also has a complex structure. The edges are fringed with bands similar to those of the opaque plate, but there are dark and bright bands within the umbra whose width reduces with the thickness of the wire. (This picture was taken in white light through a red filter. The wire diameter is 1.2 mm, and the distance from the wire to the camera is 0.5 m.)

The shadow cast by a ball or a small opaque disk is quite unusual (Fig. 128). In addition to the familiar dark and bright circles surrounding the shadow, a bright spot appears in the centre of the umbra as though there were a small opening in the centre of the disk. (For this picture we used a ball 2.5 mm in diametre and a red filter. $R_1 = R_2 = 0.5$ m.)

Diffraction refers to the phenomena that result when light does not propagate in strict accordance with the principles of geometrical optics. These phenomena can be explained by the wave nature of light. We can get a more exact description of light propagation not from the structure of the rays but from the patterns of light wave propagation themselves.

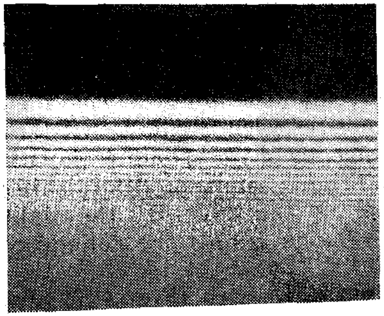


Fig. 126

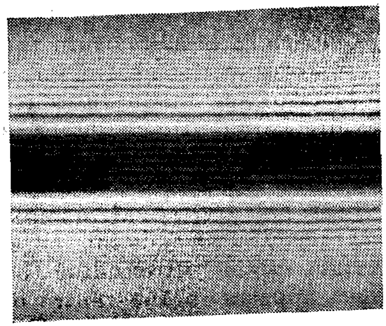


Fig. 127

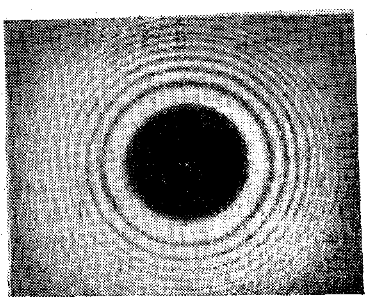


Fig. 128

Consider the circular waves that appear when a stone disturbs the calm surface of a pond. If the waves reach a log floating on the surface, a clearly defined shadow appears in the wake of the log. The shadow is bounded by the rays drawn from the point at which the stone hits the surface of the water through the ends of the log. Within the shadow, diffraction creates less noticeable waves, which scarcely disturb the pattern of the geometrical shadow. If the waves run into a pile, the wave pattern for a very short distance behind the pile does not resemble a geometrical shadow. Finally, if the waves hit a thin pole sticking out of the water, no shadow appears at all since waves move freely around small obstacles. In this case only a weak circular wave caused by the pole is visible on the surface.

Thus, sometimes straight rays accurately describe the patterns of wave propagation, and sometimes diffraction patterns dominate. The pattern depends on the relationship between the wavelength, the dimensions of the obstacle (or opening) that limit wave propagation, and the distance to the plane of observation. This relationship can be formulated as follows: if the obstacle or opening can be seen from the points of the screen on which we observe the shadow at an angle greater than the angle at which the entire wavelength can be seen from the distance equal to the width of the obstacle, then the diffraction does not strongly distort the picture of the rays. In the resulting formula $\frac{a}{R} \gg \frac{\lambda}{a}$, a is the size of the opening, R is the distance to the screen on which the shadow is observed, and λ is the wavelength. If the angles are comparable, however, or if the first angle is less than the second, i.e., $\frac{a}{R} \ll \frac{\lambda}{a}$, diffraction plays decisive role, and the rays cannot be described as linear. In optics the angles are normally comparable since visible light wavelengths are very small (from 0.7 μm for the colour red to 0.4 μm for violet). But at great distances from a thin opening or wire, the first angle may be less than the second.

Light diffraction patterns can be observed with a very simple setup. Make an opening 0.1-0.2 mm in diametre in a piece of foil with a sharp needle, and glue the foil to a piece of cardboard in which an opening has been made. The cardboard is needed only to prevent the interference of the light source (this can be a desk lamp). Attach the cardboard to a mount, and project a magnified image of the filament of the bulb onto it with a lens capable of close-ups from 4 to 6 cm away. Make certain that part of the image falls on the opening in the foil. The light cone that forms behind the screen can easily be projected onto a mat plate of glass or detected with the human eye (if the light cone catches the eye, the opening will seem dazzling). Now place objects for observation about 0.5 m away from the opening; our observations of the diffraction pattern will be made another 0.5 m behind the object. Make your observations through a weak magnifying glass or a lens capable of close-ups from 2 to 5 cm that has been fixed to a mount. Stand so that the whole lens is brightly illuminated. The diffraction pattern can be clearly seen against a bright background.

Figure 129 shows the setup, with which all the diffraction patterns reproduced in this article were obtained. We used an optical bench in the experiments. This is not mandatory, of course, although the diffraction patterns can be moved

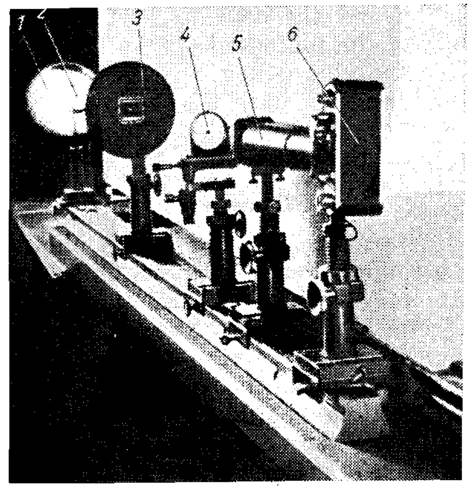


Fig. 129:

(1) lamp; (2) projecting lens, (3) point diaphragm with a light screen, (4) clamp for diffracting objects, (5) lightproof tube, (6) photographic camera without objective

more easily into the centre of the field of vision if you have supports with screw displacements.

The shadow from a straight-edged, opaque screen can be provided with the blade of a safety razor. Use two such razor blades, to make a slit 0.3-1 mm wide. A piece of wire up to 1 mm in diametre will give you the diffraction pattern of a narrow screen. The tip of a needle also produces an interesting pattern.

To produce a bright spot in the centre of a shadow cast by a round object use a steel ball bearing 2-4 mm in diametre. Attach the ball to a glass plate with a drop of glue. (The glue should not be visible beyond the contour of the ball, and the surfaces of the plate and the ball should be clean.) When the glue is dry, fix the plate in the setup. Adjust the plate until the shadow of the ball is in the centre of the field of vision. In this position both the outer diffraction circles and the spot in the centre surrounded by dark and bright circles will be clearly visible.

The diffraction patterns can easily be photographed with a camera from which the objective lens has been removed. The shadow of the object should be projected directly onto the film in the camera. To increase the resolution and the number of diffraction fringes, the opening, which serves as a light source, should be covered with a light filter. A red filter works best since there are many red rays in the spectrum of light from a conventional electric bulb. Normally, an exposure of 5 or 10 seconds is sufficient. To avoid overexposure the camera and setup should be connected by a tube with a black lining.

Displacement of the light source would cause displacement of the shadow, and hence the spot itself. Therefore, if you use a slide instead of a point source in your setup, every transparent point on the slide will cast its own, slightly displaced shadow of the ball with its own bright spot. As a result, the outer diffraction circles will diffuse, and an image of the slide will

appear in the centre of the shadow. The ball will act as a lens. The image of Planck's constant in Fig. 130 was obtained in this way. The photograph was made with a ball 4 mm in diametre. The height of the symbol $\hbar$ is 1 mm. The original slide was made with contrast film by photo-

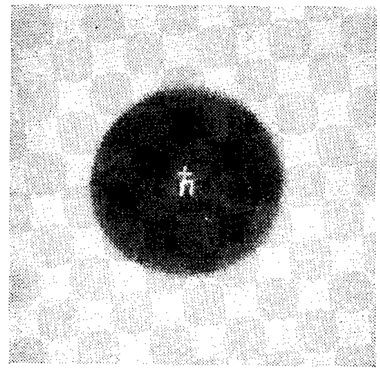


Fig. 130

graphing a letter drawn in India ink on white paper.

If you drill an opening about 2 mm in diametre in a thin tinplate, you can see how the diffraction pattern of the opening changes at various distances. Cover the opening with a light filter, and move closer to it. From a distance of 1-2 m, you should be able to see black circles in the centre of the pattern with a magnifying glass. As you move closer, the circles change to dark rings, diffusing towards the boundary of the shadow. The number of dark rings, including the dark spot in the centre, is determined by the difference in the distances travelled by the central ray and the ray from the edge of the opening. This fact can be used to determine the light wavelength if the opening diametre, the distance from the light source to the opening, and the distance from the opening to the image are known. The plane of the image can be determined by placing

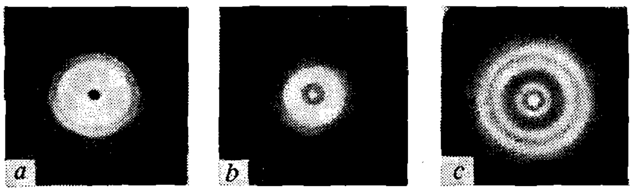


Fig. 131

a) 1 mm in diametre. $R_1=R_2=0.5$ m. Red filter. The opening shows two zones. Black spot in the centre; (*b*) 1 mm in diametre. $R_1=R_2=0.5$ m. Blue filter. The opening shows almost three zones; (*c*) 1.5 mm in diametre. $R_1=R_2=0.5$ m. Red filter. The opening shows slightly more than four zones

a needle in front of the magnifying glass and moving it until it resolves sharply against the background of the diffraction pattern. We will discuss the derivation of the calculation formula later.

You can observe the beautiful variation in the colour of diffraction circles in white light. These colours, which do not resemble spectral colours, are called complementaries. They can be observed when one spectral band is missing from the complete spectrum of white light. In this case, for example, when green is represented by a dark centre spot, the remaining parts of the spectrum, i.e. red-orange and violet, make the centre of

the picture look purple. The absence of red produces the complementary green-blue colour, and so on. Figure 131 shows examples of diffraction patterns from a round opening.

Why do we have a black spot in the centre of the pattern, which the light rays seem to reach without interference? Let us return to our observation of waves on the surface of a pond. Consider two stones thrown simultaneously into the pond and the resulting two systems of waves. Imagine points on the surface reached by the crests of the

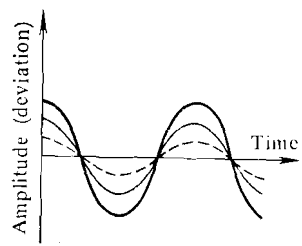


Fig. 132

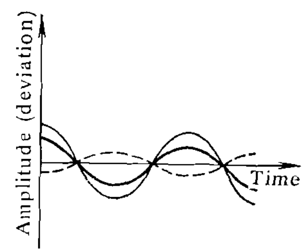


Fig. 133

two wave systems simultaneously. With time the same points will be reached by the troughs, and the waves will become larger (Fig. 132). This enhancement will occur at points that lie at various distances from the wave sources. The waves will also be enhanced at points that lie an entire wavelength, two wavelength, and so on from the source. When the crests of one wave system meet the troughs of another, the waves dampen one another (Fig. 133). This interference plays the decisive role in forming diffraction patterns.

Every point in space that is pierced by a light wave can also be regarded as a source of a secondary spherical wave (Fig. 134). If the light passes through a round opening, we can replace the light source with secondary light sources distributed over the area of the opening. All these sources will fluctuate in concord with the first wave to reach the opening. The amplitude of the

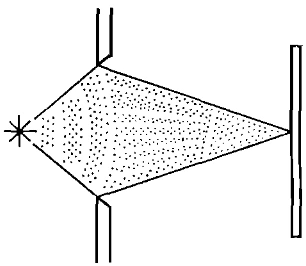


Fig. 134

fluctuations at a point behind the screen is calculated as the sum of the fluctuations caused at the observation point by each secondary source. Waves from different sources travel different distances and can enhance or dampen one another when combined.

Let us observe changes in the amplitude of oscillations around the axis of a round opening illuminated by a point source. When the distance to an observation point is very great in comparison with the diametre of the opening, the waves from all secondary sources travel almost the same distance and enhance one another when

they reach the observation point. As we move closer to the opening, the secondary waves from the sources at the edge will lag significantly behind waves travelling from the centre, and the resulting amplitude will decrease. When the ray from the edge to the observation point becomes an entire wavelength longer than the central ray, the oscillations are completely dampened (compensated), and a black spot appears in the centre of the diffraction pattern. If we move even closer to the opening, we disturb the dampening of oscillations on the axis, and the centre becomes bright again. This time the dampening will take place at a distance from the axis, and the centre of the diffraction pattern will be surrounded by a dark ring. When the ray on the edge lags two wavelengths behind the central ray, the dampening at the axis reoccurs. The diffraction pattern in this case will be a bright spot with a dark centre and one dark ring.

The dark spot in the centre will appear periodically as we move closer to the opening. We can tell how many oscillations occurred at the axis by counting the number of dark rings. The same phenomenon can be seen if we change the radius of the opening rather than the distance to it. These explanations are enough for you to derive a formula to determine wavelength.

Good luck!

To the Reader

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