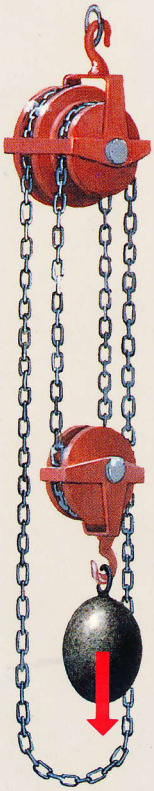
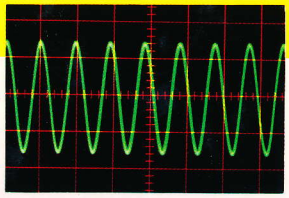
Time-Life's
Illustrated
World of Science

ENERGY AND PHYSICS





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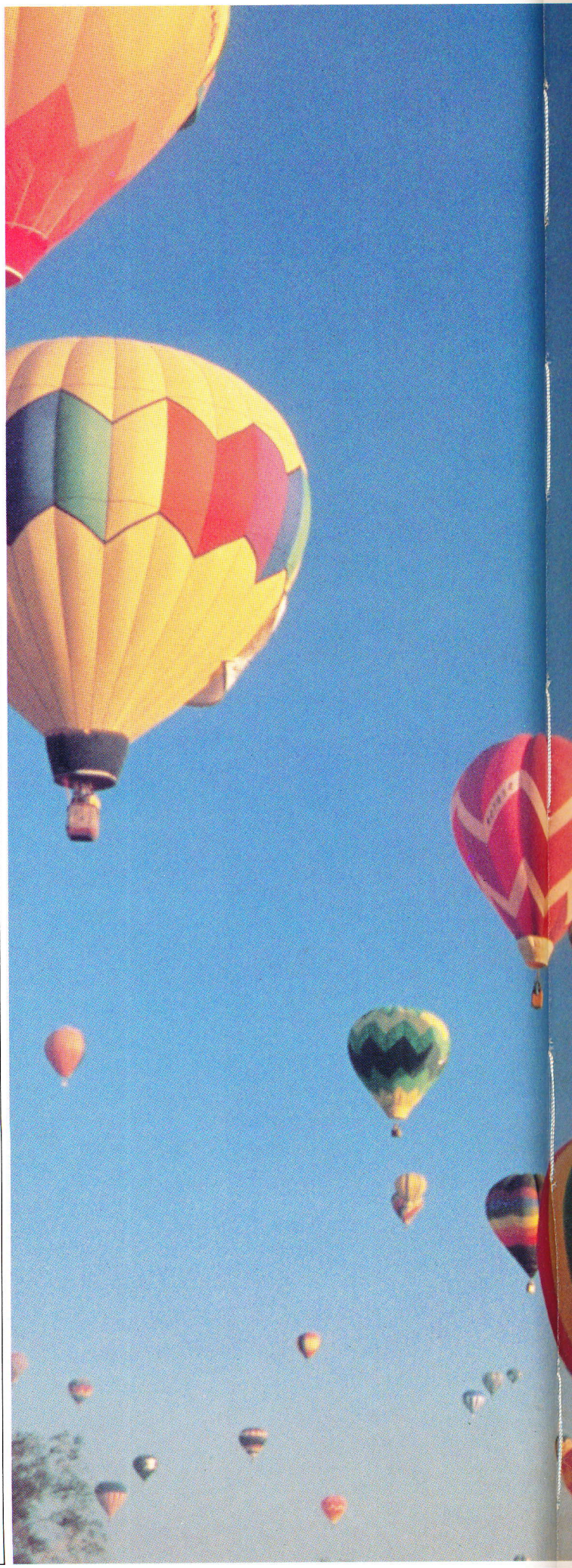
1

Force and pressure

Four basic forces exist in the universe and affect the behaviour of objects ranging in size from the subatomic to the astronomical: gravity, electromagnetism, and the strong and weak nuclear forces. Of these four, gravity shapes the very fabric of the cosmos and governs the motion of the galaxies, stars, and planets. Gravity also makes its presence felt on the more humble human scale of balloons and boats, aeroplanes and rockets.

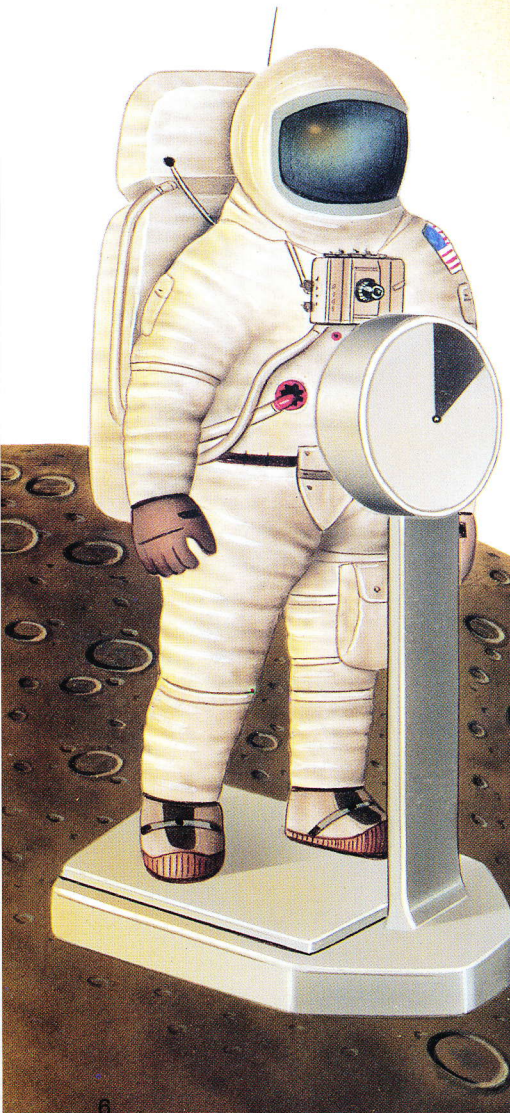
Like all forces, gravity can be measured. Physicists gauge the strength of a force by how it accelerates a body or changes the object's size or shape. Since forces have both magnitude and direction, scientists characterize the forces as vector quantities, which are represented in this book as arrows. When forces act in the same direction, their effects are magnified. When acting in opposite directions, they may cancel each other out; in such a case they are said to be in equilibrium. Force applied against a surface is called pressure and is measured according to its strength across a given area, for instance in newtons per square metre. Gases, liquids, and solids are all subject to the external pressure of the atmosphere, but they also exert internal pressure because of their molecular arrangements. In analysing phenomena, scientists therefore must frequently consider multiple forces. This book will examine these forces and explain in this chapter how they interact.



In the photograph at right, the gaily coloured balloons dotting the sky overcome the force of gravity because they are filled with hot air, which is lighter than the surrounding cold air.

Why do things weigh less on the Moon?

Objects or people, like the bouncing astronaut shown here, weigh less on the Moon than on Earth because of the Moon's weaker gravitational field. Gravity is a basic force of attraction that is spread throughout the cosmos and acts on all physical objects. The gravitational attraction between any two objects, for example a planet and a person, can be determined by knowing the mass of each item and the distance separating them. Mass, which remains constant, is a measure of the amount of matter an object contains. Weight, on the other hand, is a measure of the force of gravity on an object. The stronger the gravitational field, the greater an object's weight will be and the faster the object will be accelerated; the weaker the field, the less an object's weight will be and the less acceleration it will experience. Since gravity fields vary with the size of the objects they surround, it follows that the weight of an object is not a fixed quantity.



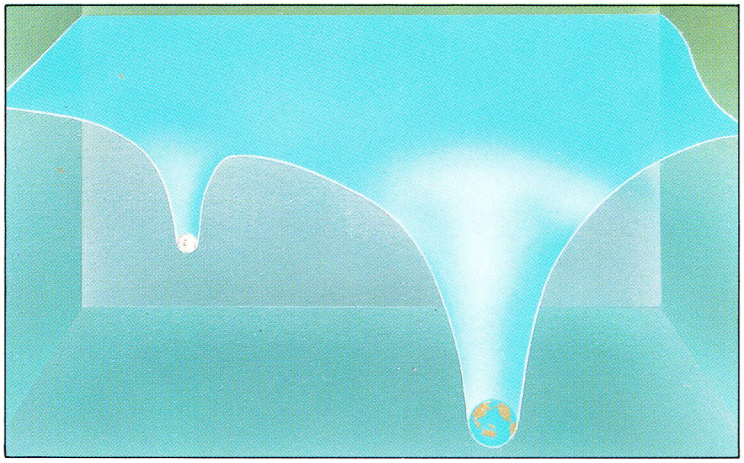
On the Moon, an astronaut's weight is diminished to one-sixth of that on Earth because the tug of gravity there is only one-sixth as strong as it is on Earth.

A matter of mutual attraction

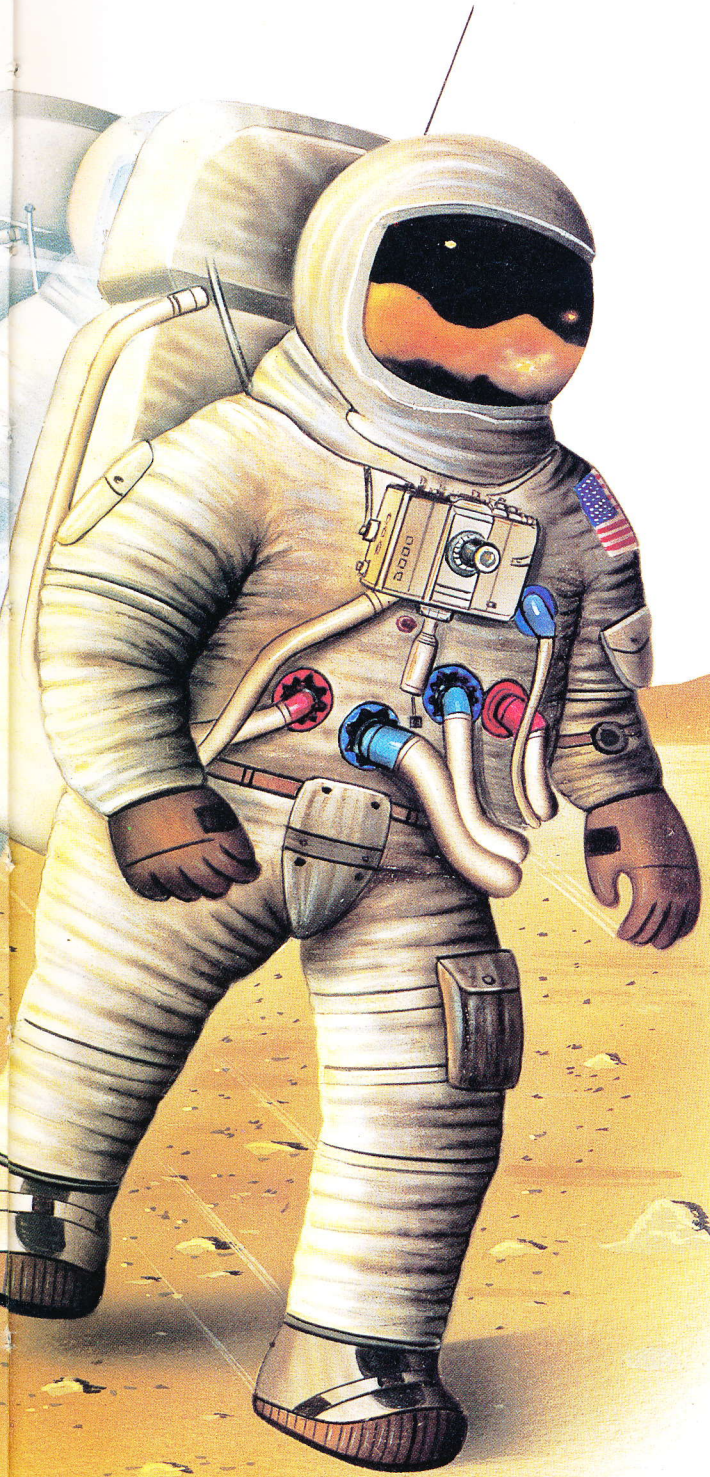
The Moon and Earth (*above, left and right*) exert gravitational pulls on bodies near their surfaces; each body exerts a corresponding pull that is proportional to its mass. The distance between the

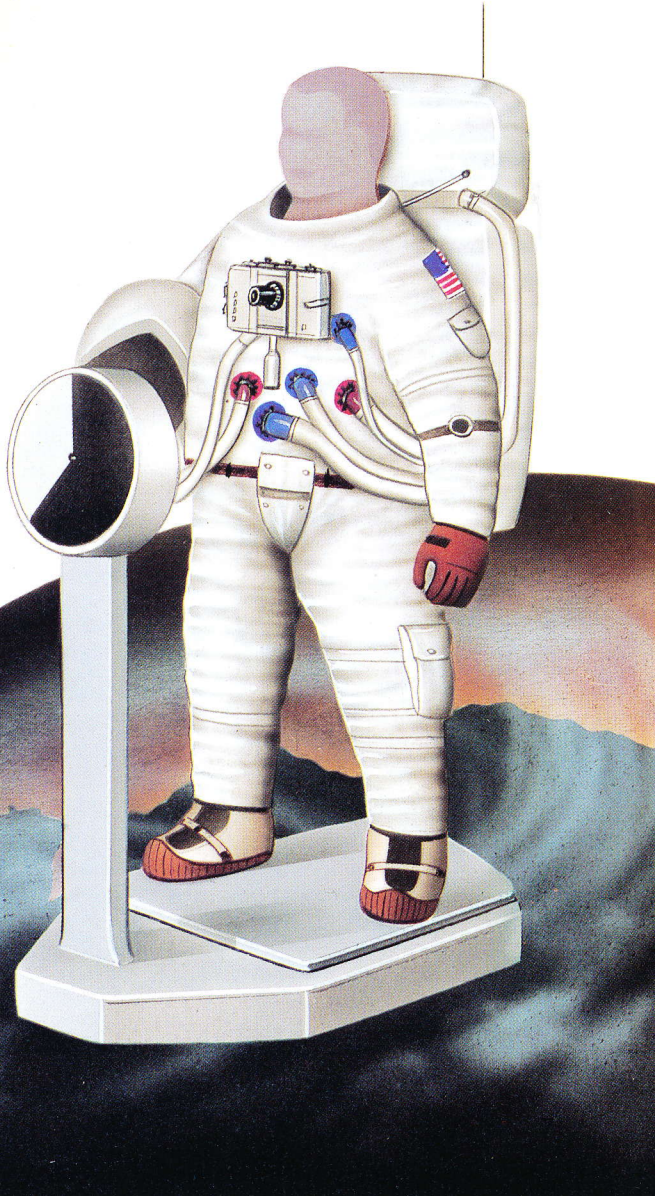
Like stones in a well

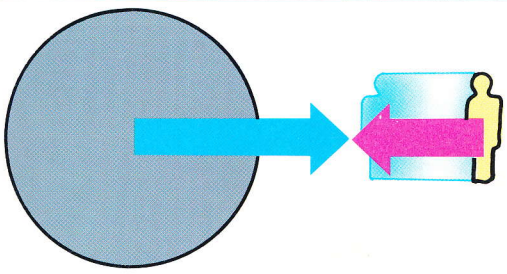
In the combined gravitational field below, the Moon (*left*) exerts a lesser force than the more massive Earth (*right*). Escaping gravity has been likened to climbing out of a well. The greater the gravity, the deeper the well and the steeper its sides.



Back from the Moon, the astronaut shown below weighs six times as much on Earth as he did on the Moon. Larger in mass than the Moon, Earth exerts a greater gravitational force.

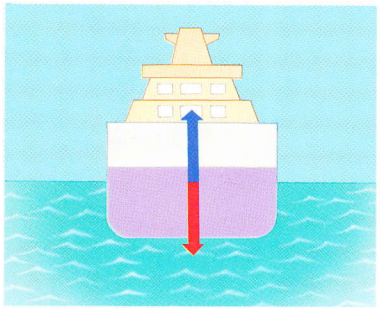


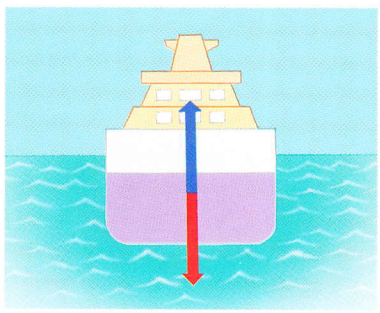




Moon and the person at left, combined with the low mass of the Moon, make for a weak gravitational bond. In the pair at right, by contrast, the great mass of Earth ensures a much stronger pull.

Why do ships float?

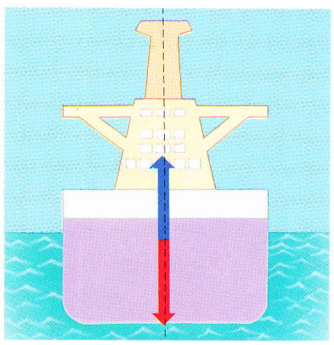




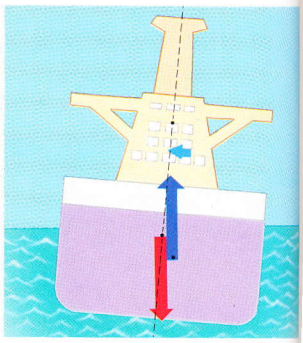
Gravity versus buoyancy

When a ship floats in the water, the forces of buoyancy and gravity balance each other out, because they are equal. A lightly loaded ship (*left, top*) rides high in the water because the force of gravity is relatively weak: The ship displaces only a small volume of water. The gravitational force of a fully loaded ship (*left, bottom*) is greater: The ship displaces a larger volume of water and sits lower in the water than the lightly loaded ship.

Maintaining equilibrium



When a ship floats upright, its centre of gravity and buoyant force are aligned. The ship is in equilibrium.

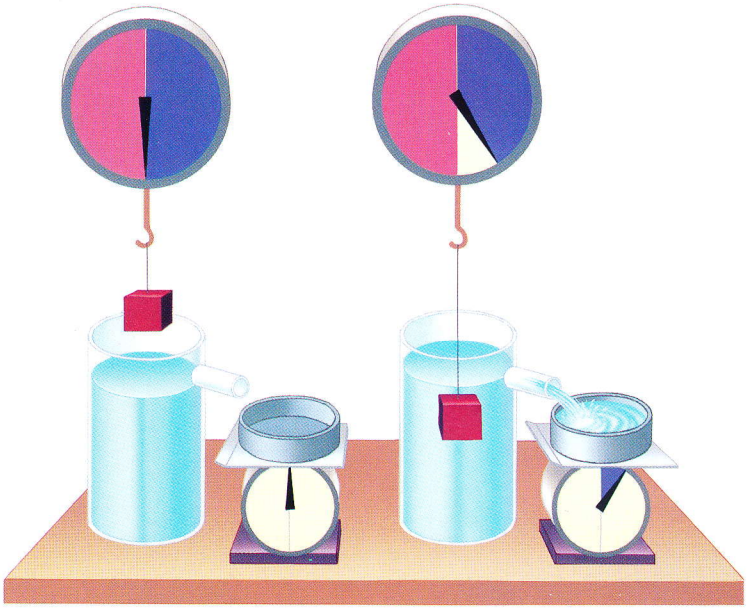


When a ship tilts, the buoyant force shifts; buoyancy's upward push and gravity's downward pull right the ship.

Ships, boats, rafts, and other objects float because of the buoyant properties of water. Like all liquids, the ocean exerts an upward pressure, which can support solid objects placed on it. In the case of ships, several factors are involved, including the density and shape of the craft and the ways in which it might be buffeted. In general, a ship will float if the volume of water that it displaces weighs more than the ship itself. The upward force of water against the hull will overcome the downward force of gravity; this downward force may be thought of as originating from a single point called the centre of gravity. Ships are said to be stable if they can be rocked by such forces as winds and waves and return to an even keel. If a ship is improperly designed or loaded, these disturbances could lead to an unstable ship, which might sink.

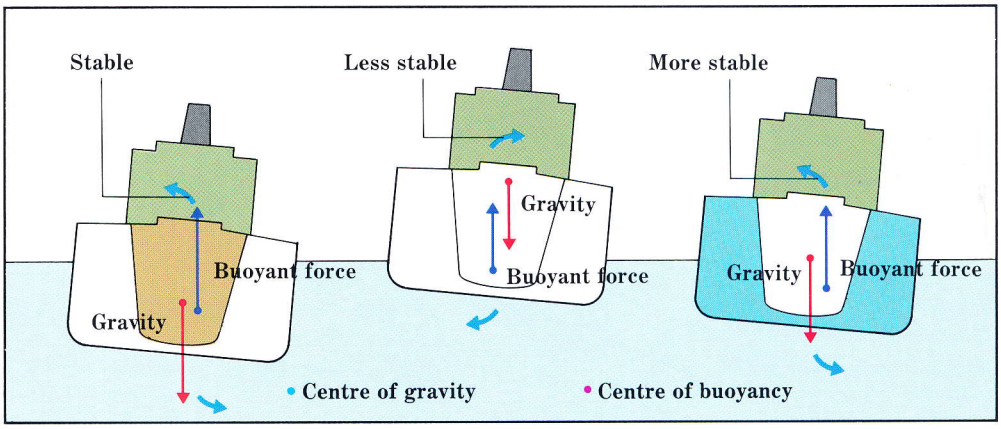
Archimedes' principle

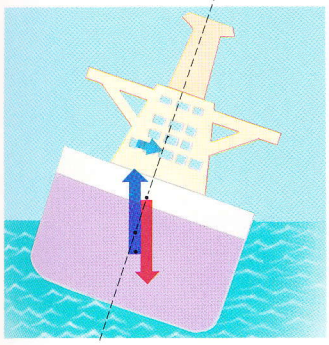
The cube below, hanging from a spring scale, weighs less in water (*right*) than in air (*left*). The cube displaces a volume of water equal in weight to the amount by which its weight has been reduced. The relationship between the volume of a submerged mass and the force that buoys it up was first described by Greek mathematician Archimedes in the third century BC.



Shifting the centre of gravity

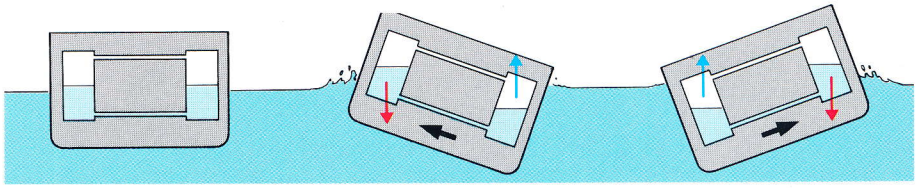
Three views show how loads affect a ship's stability. A full hold in the ship at right brings the centre of gravity and the centre of buoyant force close together, making the ship stable. Tipped by waves, the ship easily rights itself. In the empty ship in the middle, the centres of gravity and of buoyancy have moved far apart, and the ship is unstable. At far right, the weight of flooded ballast tanks restores balance.



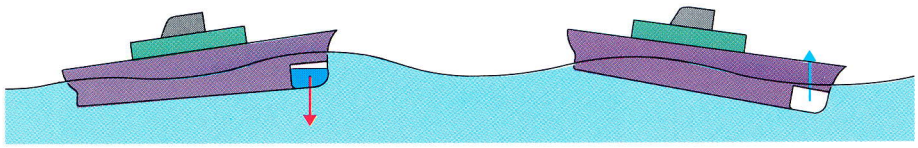


If a tilting ship's centre of gravity moves too high and lies too far from the centre of buoyancy, the ship will capsize.

Devices that reduce motion



A pair of hull tanks (*above*) helps to reduce rolling. The shifting weight of water flowing between the tanks counteracts the sideways push of waves.

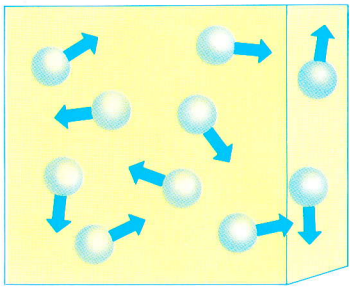


A bow tank that alternately takes in and loses water will reduce the pitching of the ship in rough seas.

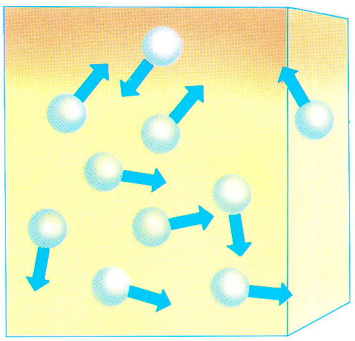
How do balloons stay up in the air?

Balloons rise because the gas with which they are filled is lighter than the surrounding air. Many gases, such as hydrogen and helium, are less dense than air. This means that, at a given temperature, they have less mass than the same volume of air. When these lighter-than-air substances are pumped into a balloon, the balloon will rise, as long as the total weight of the envelope, basket, cargo, and lines is less than the weight of the air that the balloon displaces. (Since air is considered a fluid in physics, the same principle governing objects floating in a liquid applies here.) Hot air, which is less dense than cold air, also rises. Although hot air is not as light as some gases, it is safe and easy to produce with jets of burning propane mounted under the mouth of the balloon's envelope; the envelope is usually made of lightweight material such as tear-proof nylon. Hot air balloons typically stay aloft for several hours, but without additional heating of the air inside the envelope, they will gradually lose altitude.

3 **Pilots maintain** altitude or add upthrust by refiring the burners. As long as the air inside the envelope is hotter than that outside, buoyancy overcomes gravity.

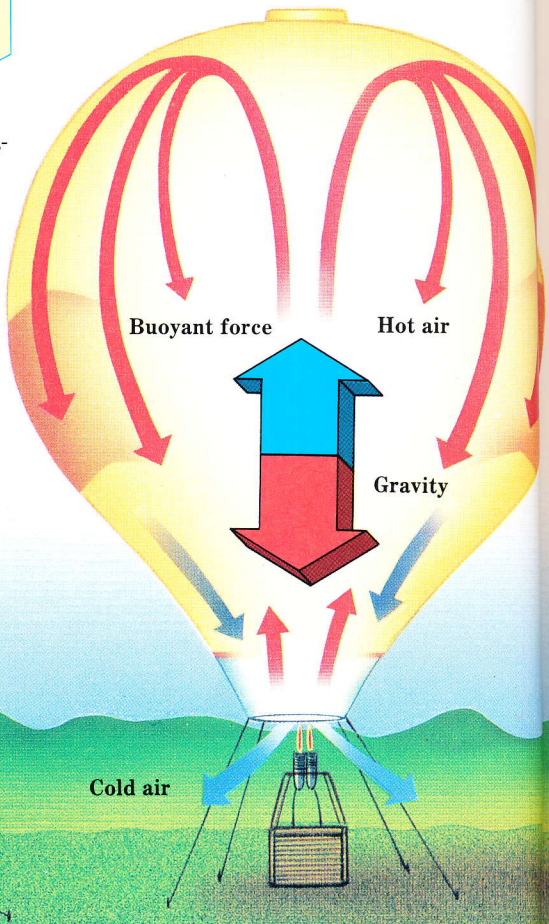


When the air is cold, molecules move slowly and bunch closely together.



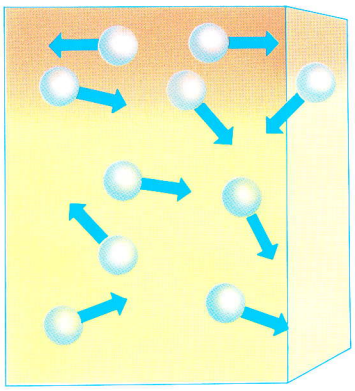
When the air is heated, molecules speed up and separate, filling a larger volume.

2 **Hot, lightweight air** (*below*) rises inside the envelope and flows down the sides. Cold air is forced out of the mouth. Its weight reduced, the balloon rises.

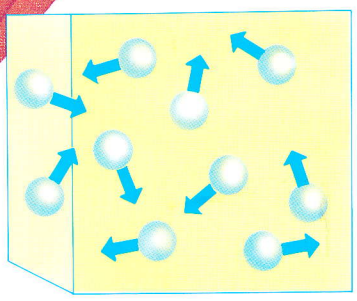


1 **A balloon** lies on its side. Propane jets are heating the air inside, which will cause the envelope to inflate and rise into the air.

4 The balloon descends as its air cools and contracts. Pilots can speed up the descent by letting hot air out of an opening in the top.



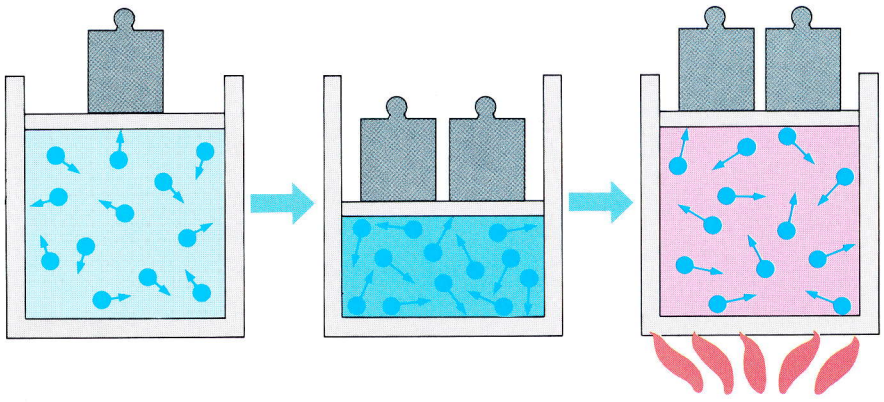
As the heated air continues to expand, it becomes less dense.



With cooling, molecules slow down, volume shrinks, and density increases.

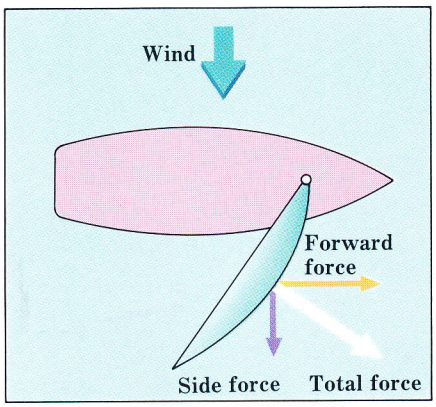
A three-way relationship

The pressure, volume, and temperature of a gas are related. At room temperature (*near right*), the motion of air molecules within a container creates a certain pressure. When the volume is reduced by half (*centre*), the internal pressure doubles. When the air is heated (*far right*), its pressure rises and the volume expands in proportion to the temperature increase.

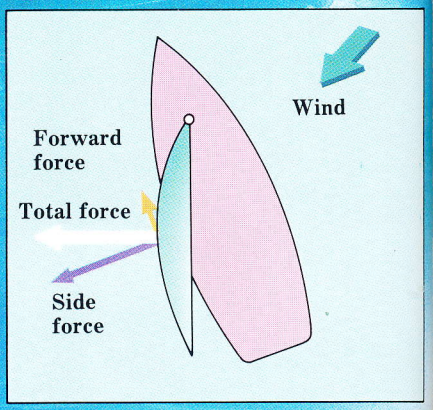


How can a boat sail into the wind?

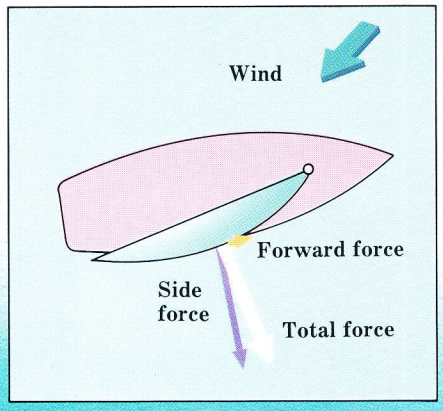
A sailing boat travelling in the direction of the wind is subject to fairly simple pressure from the wind against its sail; this pressure pushes the craft along. But sailing against the breeze exposes the sail to a more complex set of forces, as wind tunnel studies have revealed. When the oncoming air moves past the sail's concave, or curved-in, back side, it is slowed, while around the billowing front side the air flows more rapidly. This creates a zone of high pressure behind the sail and a low-pressure zone ahead of it. The difference in pressure on the two sides creates motion, which pushes the boat forward, angled to the wind.



A boat that lies roughly 90° to the wind—a position called sailing on a reach—moves rapidly ahead. The boat is subject to forward and side forces.



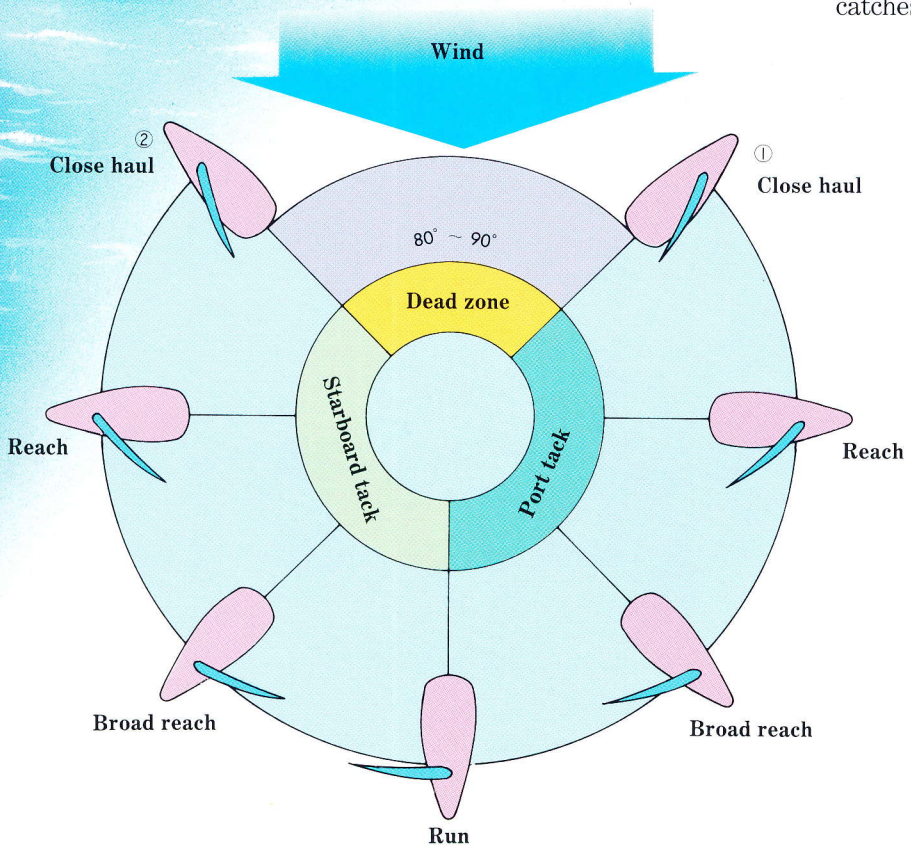
Sailing more directly into the wind, the boat slows, as the forward force is reduced and the side force increases.

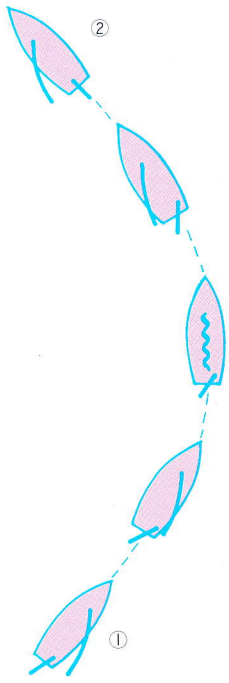


The closer the sail is held to the stern, or rear, of the boat, the more slowly the boat advances, in part because of the strong sideways force.

Zigzagging into the wind

A boat cannot head straight into the wind but proceeds in a series of short, angling moves called tacks. Wind flowing over the boat's left side (1) defines a port tack, and over the right side (2), a starboard tack. To follow the fastest course, the sailor attempts to maximize speed by adjusting the sail positions, as shown below left. To minimize the distance moved off a straight line, the boat travels by tacking to port and starboard. As the boat changes direction, the sail swings across, flapping briefly as it faces into the wind (*below, middle*). The boat slows down in this so-called dead zone until the wind again catches the sail on the opposite side.

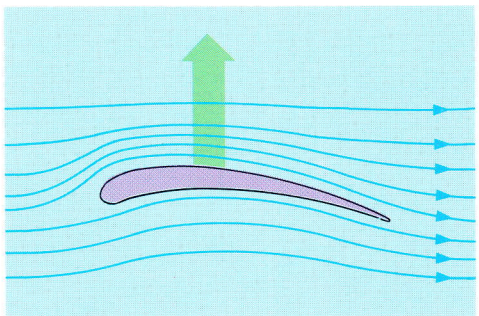




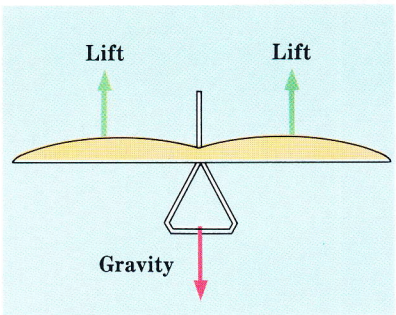
How do hang-gliders fly?

The aerodynamic properties of the modern hang-glider, which was invented in the 1950s by NASA scientist Francis Rogallo, resemble those of standard aircraft. Launched from a cliff or steep hillside, the moving wing of a glider like the one at right alters the flow of air, which streams more rapidly over the top than over the bottom surface. This creates a low-pressure zone above the wing and a high-pressure zone underneath, resulting in a force called lift that propels the wing upward. Eddies of air along and behind the wing cause drag, which works to counteract lift. As the front of the wing is angled upward, both lift and drag increase. At too steep a pitch, the drag on the wing exceeds the lift, and the glider stalls and spins toward the ground out of control.

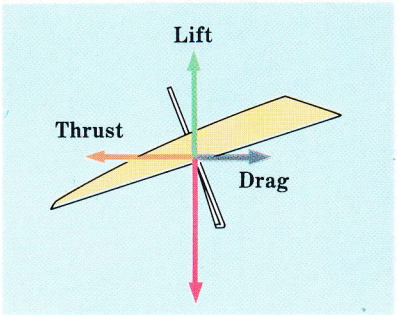
Forces acting on a glider



At sufficient speed, a hang-glider (*purple*) has enough lift (*green arrow*) to counteract gravity. Favourable winds allow gliders to soar for hours.



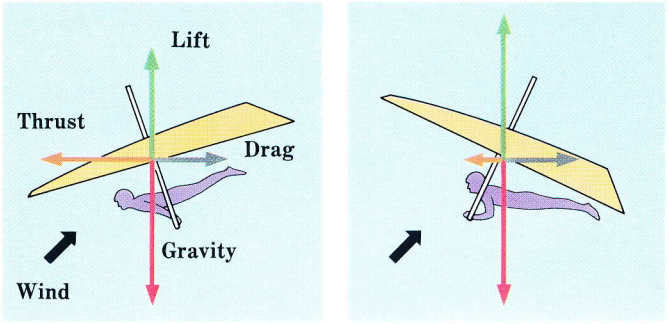
The total lift on the wing must exceed the force of gravity, resulting from the glider's weight, for the craft to remain aloft.



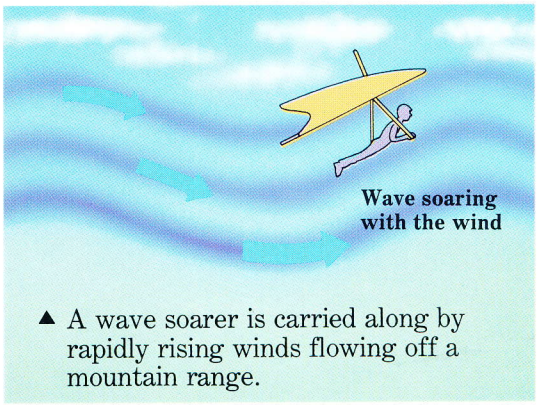
A hang-glider remains in flight only if the wing is adjusted to balance the forces that act on it.

Flying high

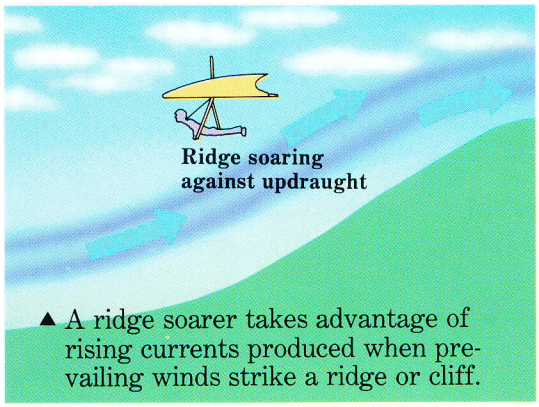
A pilot hanging from a harness attached to the wing adjusts his angle of flight by moving the control bar forward. This raises the wing (*far right*), causing the glider to rise and lose speed. Pulling back the bar prompts descent.



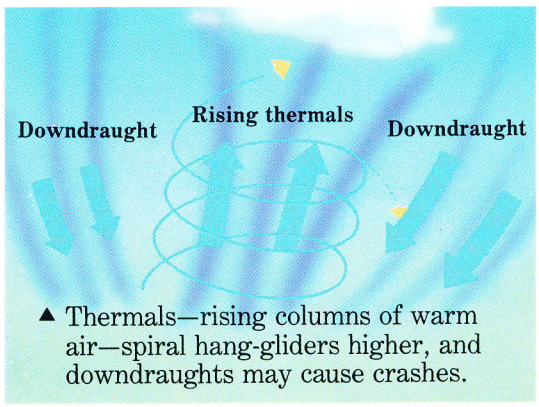
Three types of soaring



▲ A wave soarer is carried along by rapidly rising winds flowing off a mountain range.



▲ A ridge soarer takes advantage of rising currents produced when prevailing winds strike a ridge or cliff.



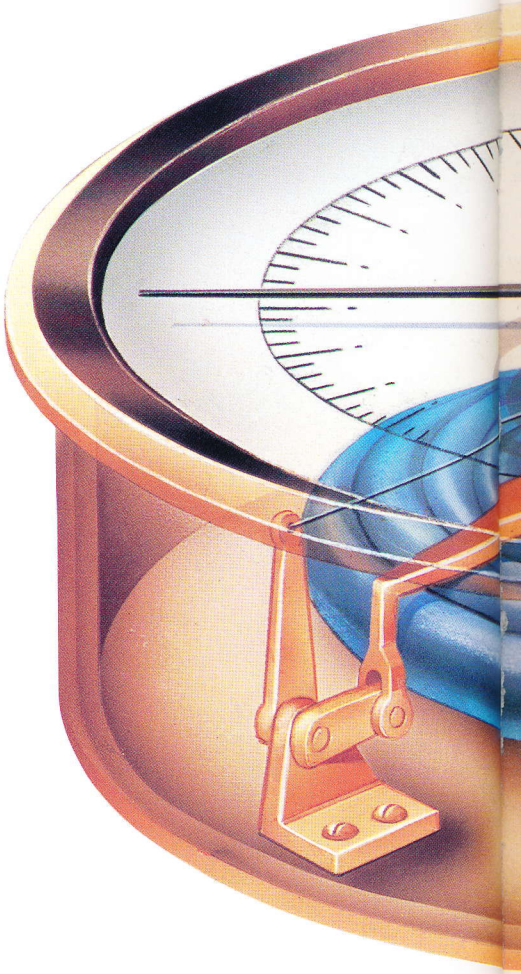
▲ Thermals—rising columns of warm air—spiral hang-gliders higher, and downdraughts may cause crashes.

What do barometers measure?

Barometers are instruments that measure atmospheric pressure. This pressure refers to the weight of the atmosphere as it presses on everything at Earth's surface. Since there is less overlying atmosphere at higher elevations, for example on a mountain top, the pressure decreases with altitude. Atmospheric pressure also varies when air masses making up cold and warm fronts move through. Thus, barometers monitor the weather.

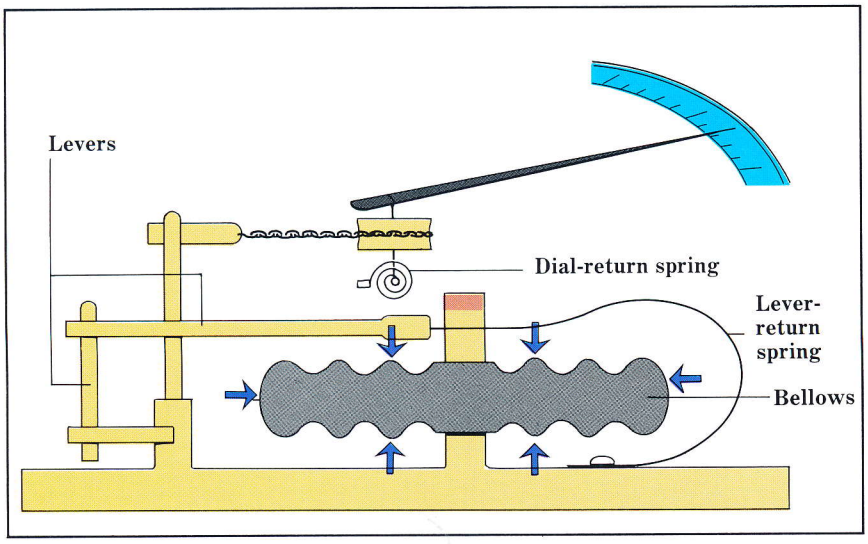
Two main types of barometers have been developed, the mercury-filled and the aneroid, or liquid-free, barometer. The mercury barometer, invented in 1643 by Italian scientist Evangelista Torricelli, uses a glass tube filled with mercury, which rises and falls as atmospheric pressure increases or decreases. The aneroid barometer, like the one shown at right, was invented in 1843 by French scientist Lucien Vidie. These aneroid barometers use small, nearly airless bellows made of corrugated metal, which act like diaphragms (*diagram below*). A sensitive mechanism translates the up-and-down motion of the bellows into the circular movement of a pointer, which in turn registers the motion on the calibrated face of the instrument.

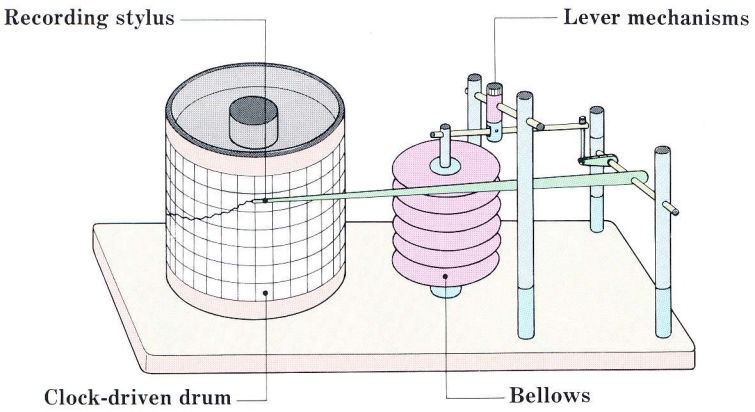
An aneroid barometer



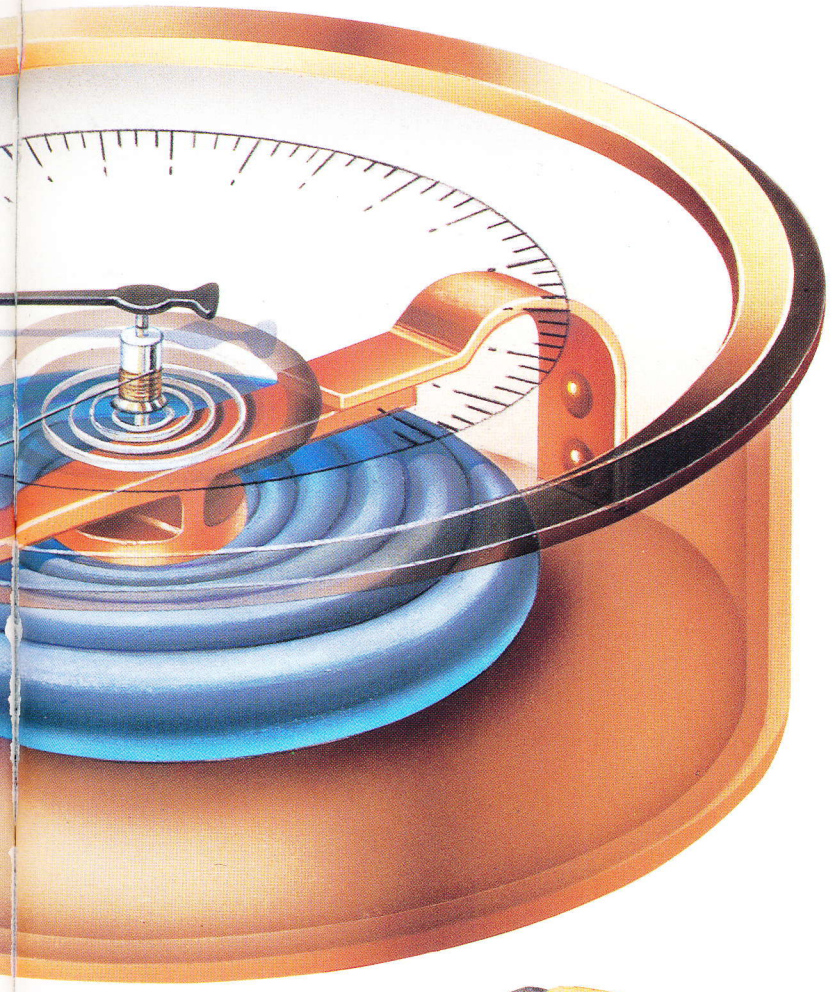
The heart of an aneroid barometer

A series of levers inside the barometer magnifies the small motions of the expansion and contraction of the bellows. Most aneroid barometers are less than 20 centimetres across.

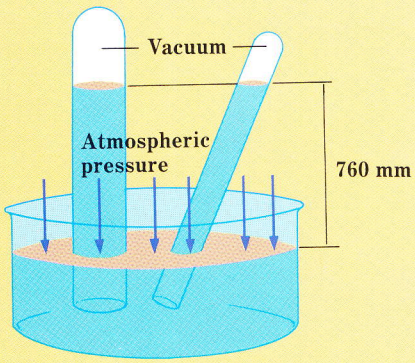




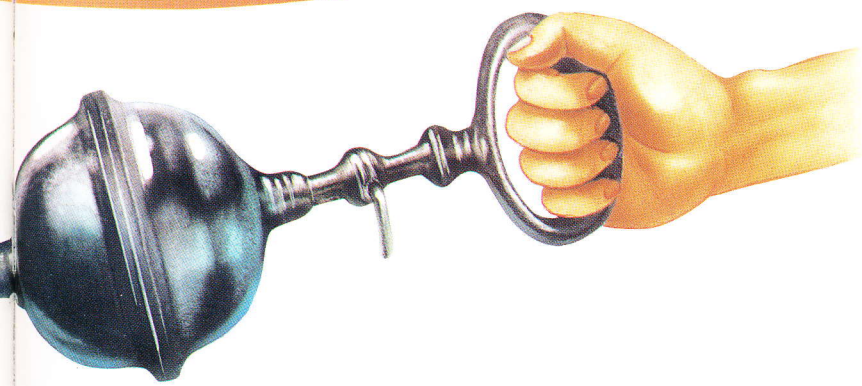
An aneroid barograph. The fine stylus of a barograph charts a continuous record of atmospheric pressure on a rotating drum.



Torricelli's barometer



Atmospheric pressure causes mercury to rise and fall in these tubes. The height of the mercury depends only on the atmospheric pressure, not the size of the tube. At sea level, the mercury rises to about 760 millimetres. Millimetre of mercury, or mmHg, is a commonly used unit to measure atmospheric pressure.

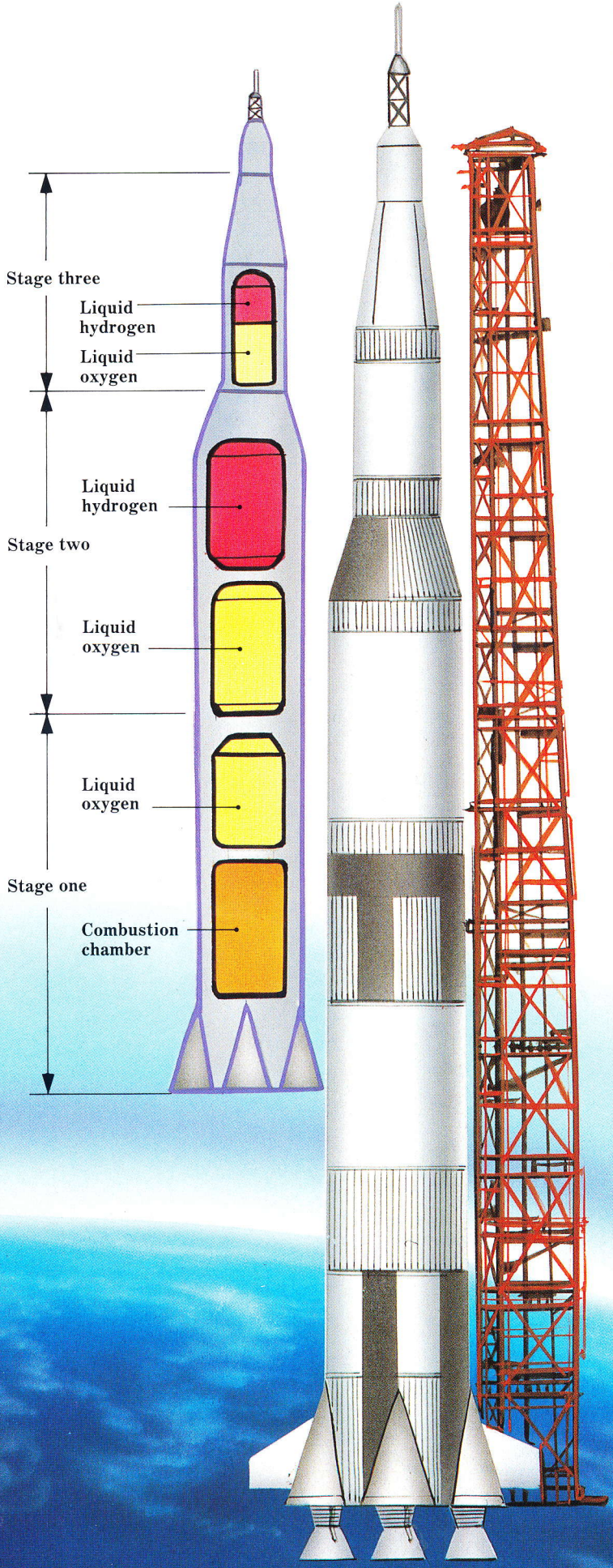


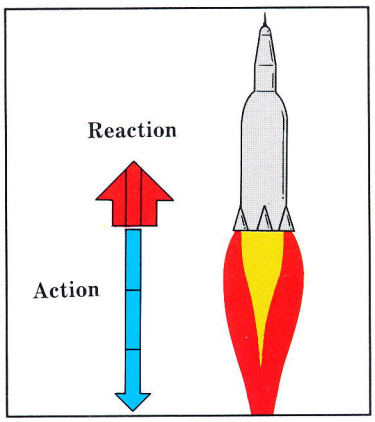
Magdeburg hemispheres

Two simple metal hemispheres demonstrate the existence of atmospheric pressure. All air has been pumped out, creating a vacuum inside. Now the atmospheric pressure, pushing on the outside, makes it impossible to separate the halves.

How is a rocket launched?

Rockets are blasted into outer space by burning liquid or solid propellants. Ignited in reinforced combustion chambers, these propellants, usually consisting of a fuel and an oxidant, create enormous amounts of pressure and heat, which propel exhaust gases groundward through expansion nozzles. As the exhaust blows down, the rocket soars up. The phenomenon is described by Newton's third law of motion, which states that for every action there is an equal and opposite reaction. Because liquid fuels are easier to control than solid ones, they are preferred in rockets like the Saturn V shown at left. This three-stage rocket burns thousands of metric tons of liquid hydrogen and oxygen to boost a capsule into orbit.

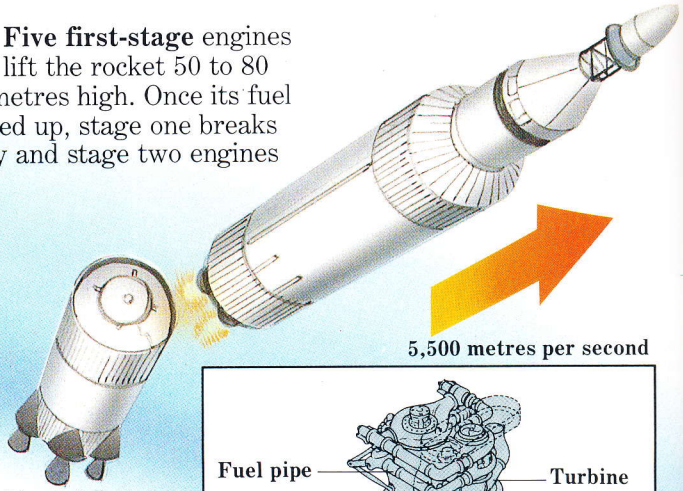


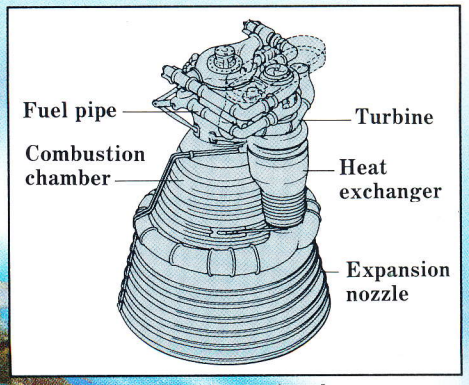


Escaping gravity

To rise off the ground, a rocket's thrust must exceed its weight by about 30 percent. At the same time, if the capsule is to go into orbit, it must reach a velocity of about 8,000 metres per second. Rockets generate thrusts of about 7 billion newtons per square metre.

1 **Five first-stage** engines lift the rocket 50 to 80 kilometres high. Once its fuel is used up, stage one breaks away and stage two engines fire.

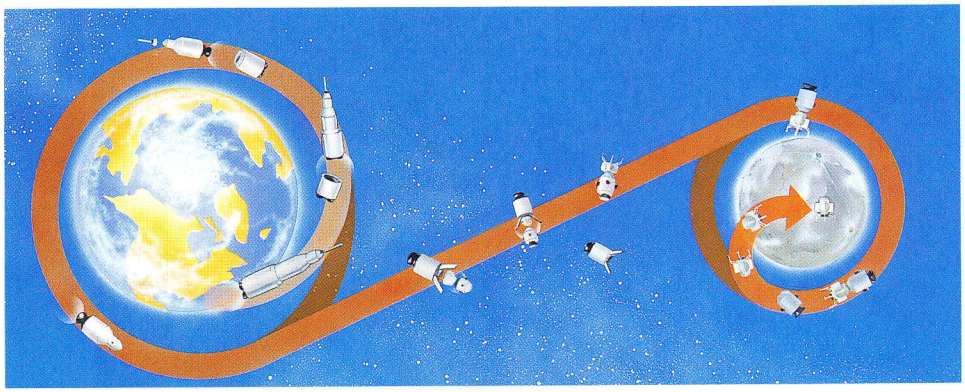




A first-stage F-1 engine burns fuel and funnels exhaust out.

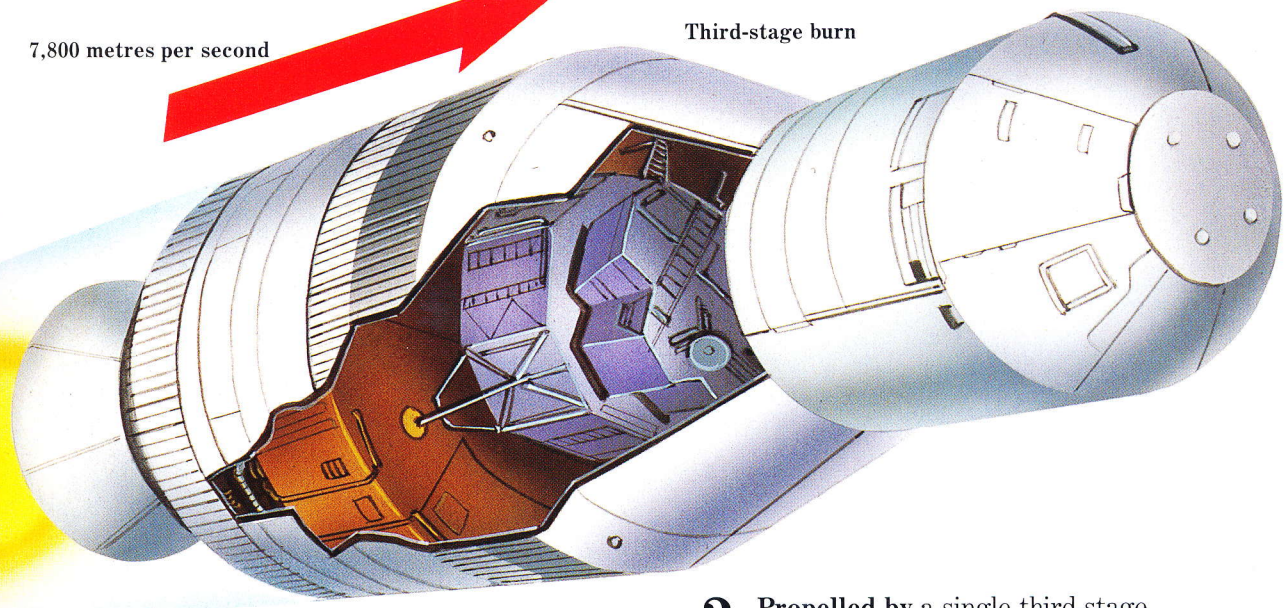
A trip to the Moon

Once in orbit, the Apollo is shot toward the Moon. Then stage three drops, the unit composed of command and service modules goes into a 100-kilometre orbit around the Moon, and the lunar module lands. After ferrying the landing team back, the lunar module will be scuttled.



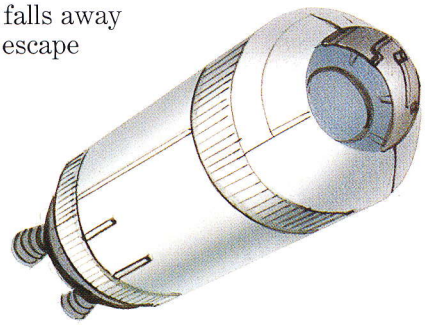
7,800 metres per second

Third-stage burn



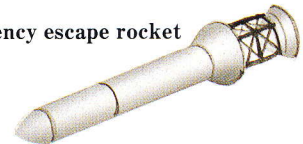
3 **Propelled by** a single third-stage engine, the rocket moves an Apollo spacecraft toward temporary Earth orbit roughly 320 kilometres above the ground. Shortly, the engine will reignite, boosting speed to about 11,000 metres per second and sending the craft toward the Moon.

2 **About 12 minutes** after lift-off, stage two has carried the rocket more than 160 kilometres above ground level and falls away empty. The emergency escape rocket also separates.



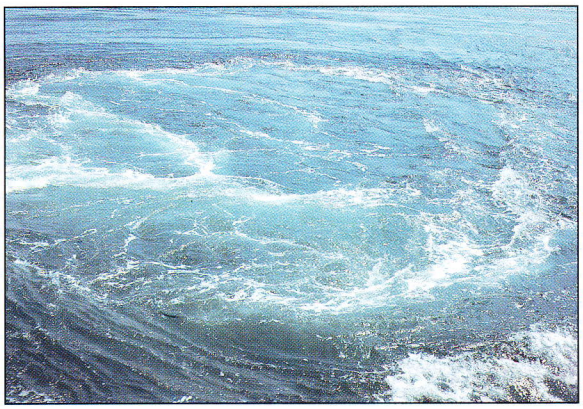
Jettisoned second stage

Emergency escape rocket



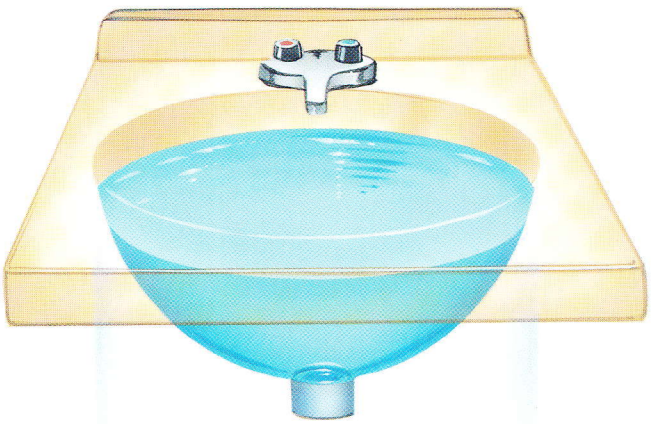
What causes whirlpools to form?

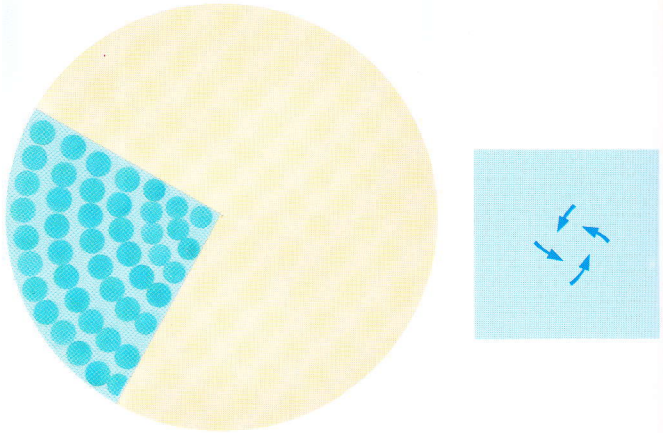
Natural whirlpools, like the one pictured below, form in oceans, streams, and rivers. They are caused by the interaction of tides or currents, or the presence of objects that deflect the flow of water. But whirlpools may also form when bodies of liquid, like water in sinks or baths, are emptied down a drain and the water flows out in a spiral. Such a whirlpool, technically called a vortex, is the result of the motion of the individual molecules that make up the liquid. Both gravity and viscosity, or resistance to flow, come into play, as described in the step-by-step drawings at right.

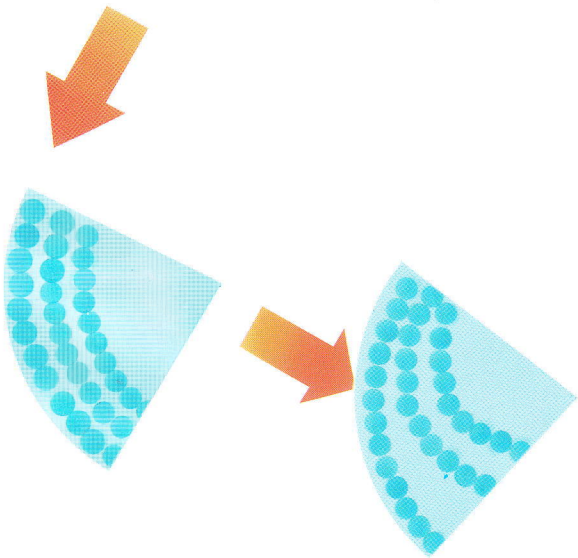


A whirlpool forms in the ocean.

1 When the drain opens, the water molecules immediately above the drain are pulled down by gravity (*below*). At the same time, resistance to the flow forces the molecules to move in a horizontal direction.

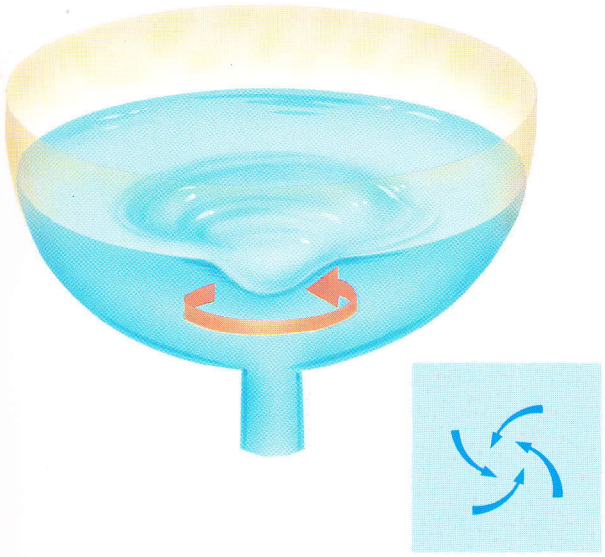




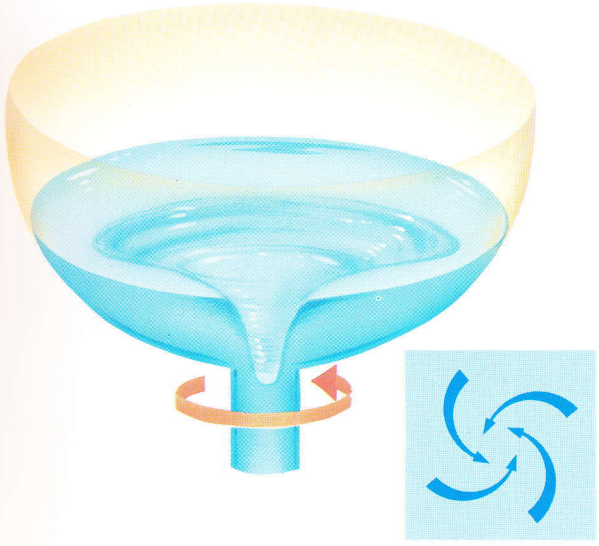


Friction and viscosity

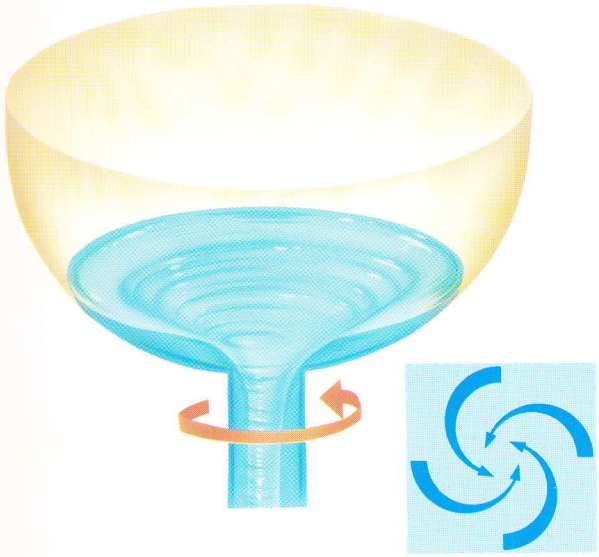
The pie diagram (*right*) traces the path of water molecules as they are set in motion. Gravity pulls down the molecules nearest to the drain. Viscosity acts against the pull and the force of friction acts on the surrounding water molecules so that they align and begin to move in tandem.



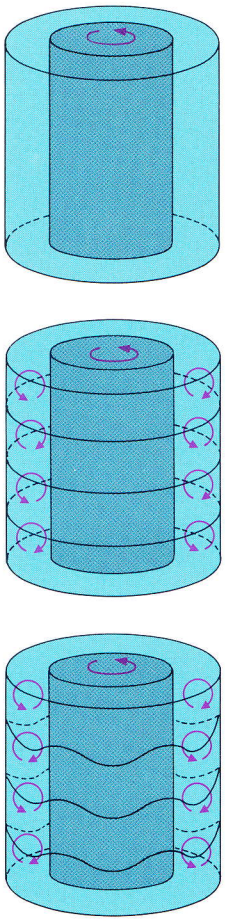
2 **Once the water** starts to move in a circular path, other water molecules follow. The closer the particles are to the drain, the faster they move. Those farthest from the centre travel most slowly.



3 **Water spiralling down** the drain forms a depression on the surface of the water, and a column of air builds at the centre of the whirlpool.



4 **When the water level** in the sink decreases, the air column reaches deeper into the pipe. The vortex builds until all the water has drained.



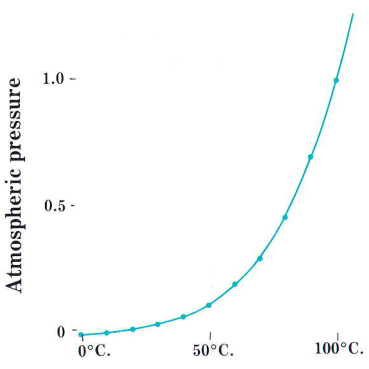
Frictional flow

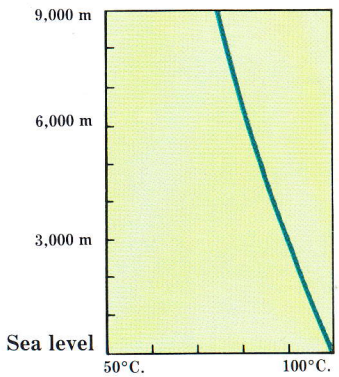
Water between two cylinders will follow the rotation of the inner cylinder and will spin faster the closer it is to the cylinder. The different speeds create waves. Eddies form as slow-moving water is taken away by faster flows.

Why does water boil faster than normal at high altitudes?

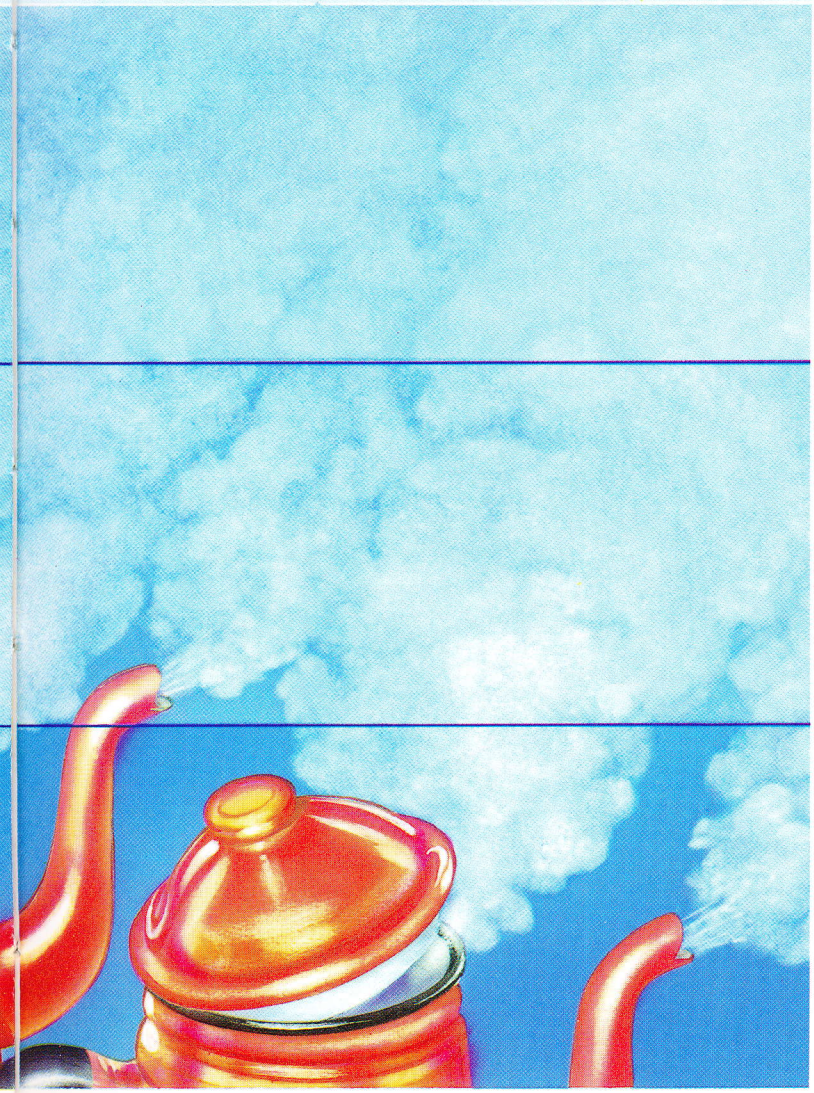
A factor of heat and height

The graph at near right shows the relationship between vapour pressure and temperature. At high temperatures, vapour pressure rises rapidly. Water boils when vapour pressure just exceeds atmospheric pressure. On the other hand, as atmospheric pressure drops, so too will the boiling point. The graph at far right compares altitude with the boiling temperature of water. The higher the altitude, the lower the temperature at which water will boil.



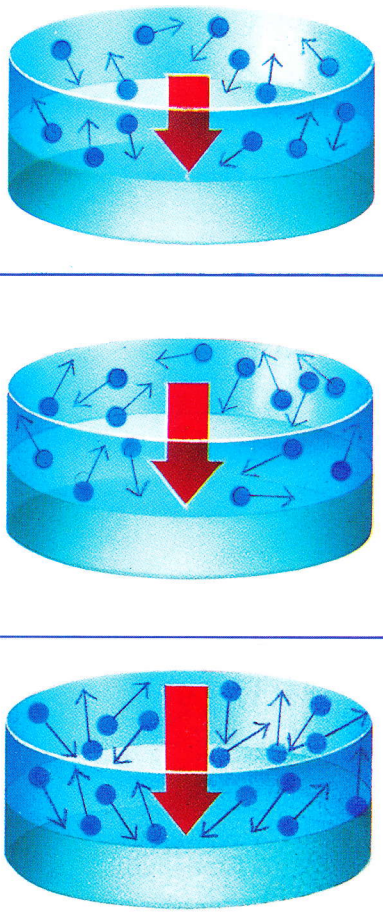


At sea level, water heated to 100° Celsius begins to boil, which means that bubbles of water vapour form throughout the liquid and rise to the surface. This happens because, at that temperature, the vapour pressure of the water slightly exceeds the atmospheric pressure. At higher altitudes, atmospheric pressure is much lower and water boils at lower temperatures. Conversely, if the pressure on a liquid is increased, for instance below sea level or in a pressure cooker, the boiling point is at a higher temperature. The illustration below shows boiling temperatures at various altitudes.



Kinetic energy

Kinetic energy, or the energy of motion of molecules, plays a role when water changes into a gas. When the energy level is high, many molecules evaporate, escaping the bonds that hold them in a liquid state. Under low pressure, below, the molecules acquire enough energy to form gas bubbles for boiling without adding a lot of heat. Closer to sea level, more heat is needed *(red arrow, bottom)* for evaporation to take place.

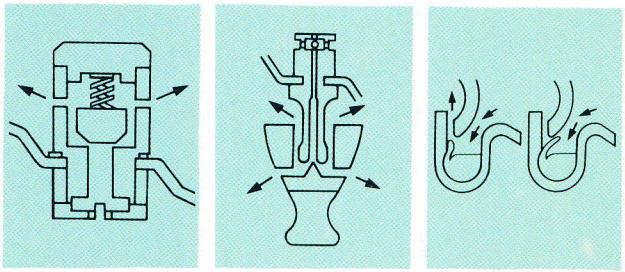


Lower atmospheric pressure

Higher atmospheric pressure

Speeding up cooking time

Pressure cookers, as at right, create a constant, elevated pressure inside. At sea level, the airtight pots boost the temperature at which water boils to 121° Celsius. Higher temperature means that foods cook faster, saving time.



Cutaway views show pressure cooker mechanisms that prevent explosive pressures from building up. The emergency safety valve (*left*), the regulator (*centre*), and the packing at the rim (*right*) all help to control pressure by allowing steam to escape.

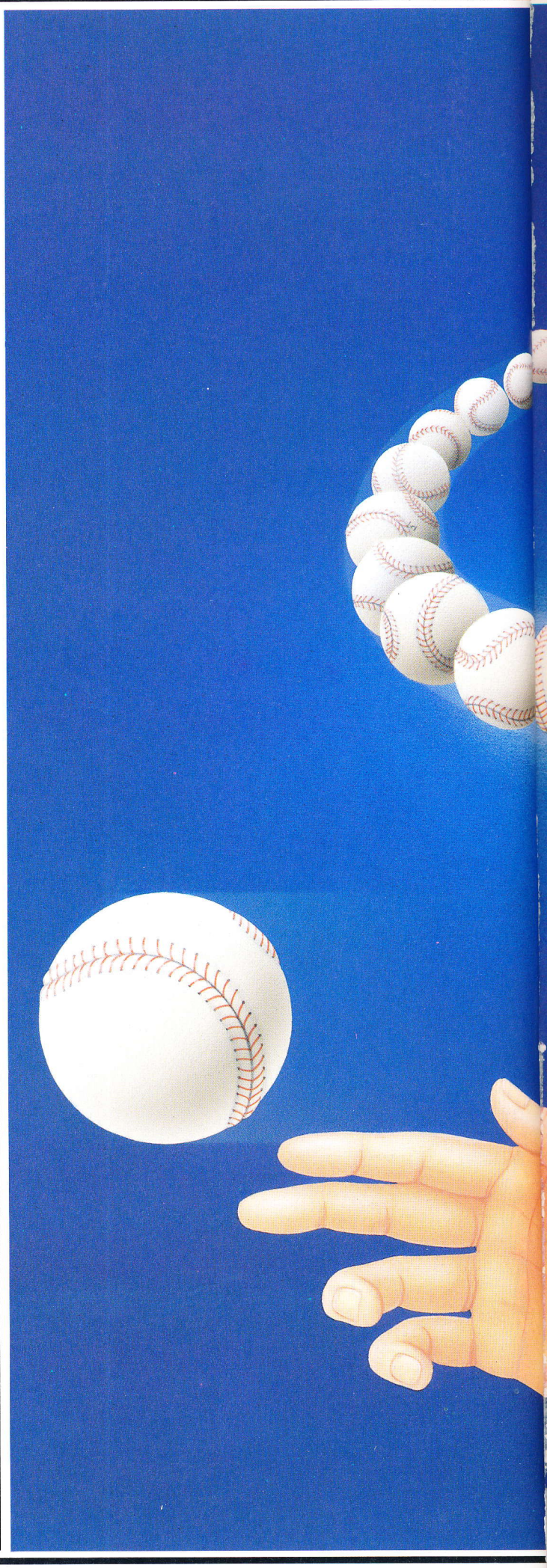
2

Gravity and motion

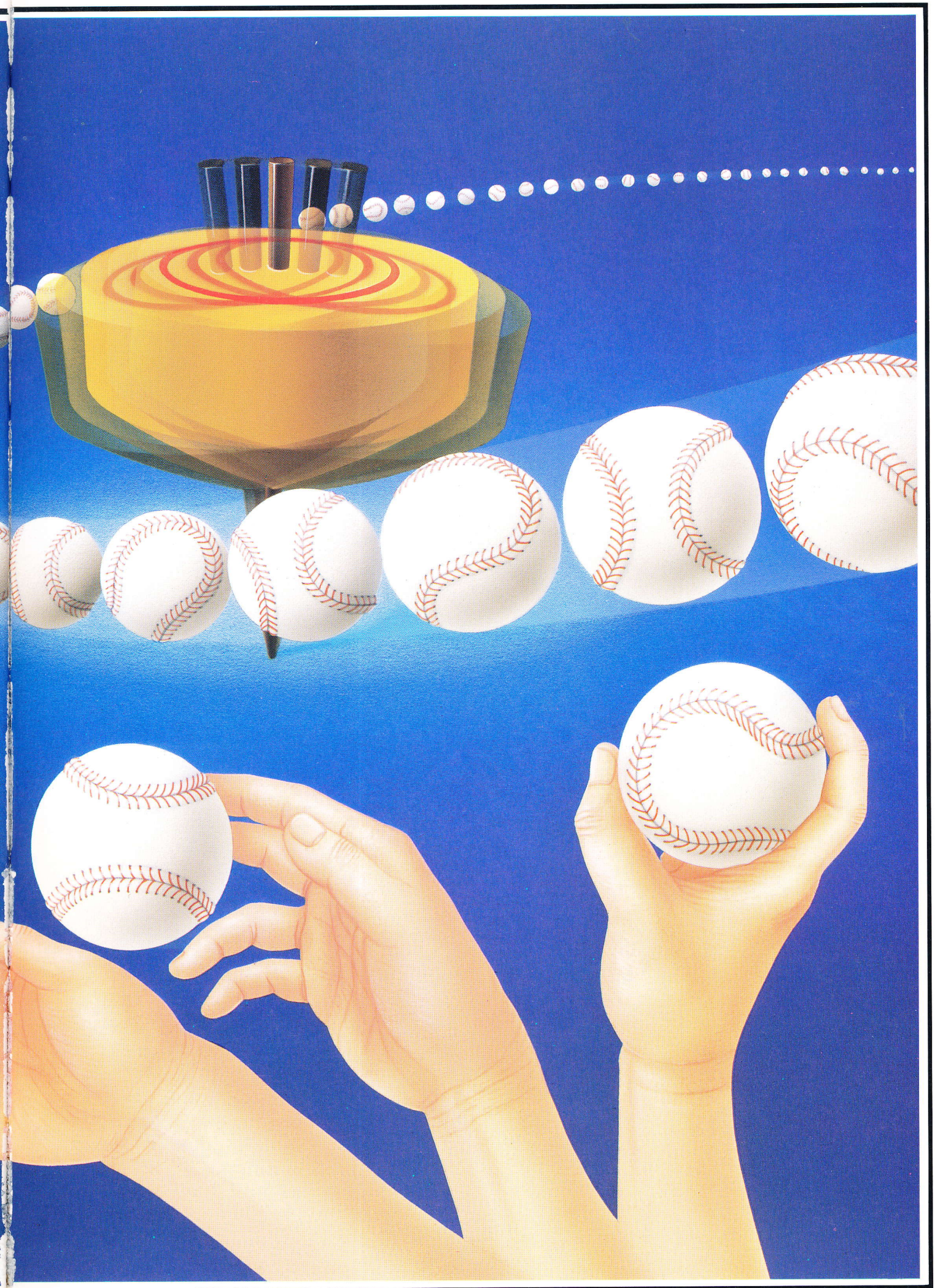
The motion of everything in the universe—from atoms and molecules to stars and galaxies—is governed by a few fundamental laws. The best formulation of these laws comes from English physicist Sir Isaac Newton, who in 1687 shook the scientific world with his book *The Mathematical Principles of Natural Philosophy*. In addition to describing a theory of universal gravitation, this book listed the three laws of motion.

Newton's first law of motion states that moving objects continue to move in a straight line and objects at rest remain at rest, unless acted on by an outside force. Called the law of inertia (*pages 28-29*), this principle plays a role in moving bodies as diverse as roller coasters and satellites. The second law describes how a force acting on an object causes acceleration. The amount of acceleration is determined by both the size of the force and the mass of the object. The third law states that for every action there is an equal and opposite reaction. In the case of rockets, it is the combustion of fuel—the action—that provides the thrust—the reaction—necessary for liftoff.

Although Newton's laws are now so familiar that they are taught in most schools, when first published they were nothing short of astounding. Such seemingly unrelated phenomena as the falling of an apple and the orbiting of planets around the Sun were from then on described under one theory.



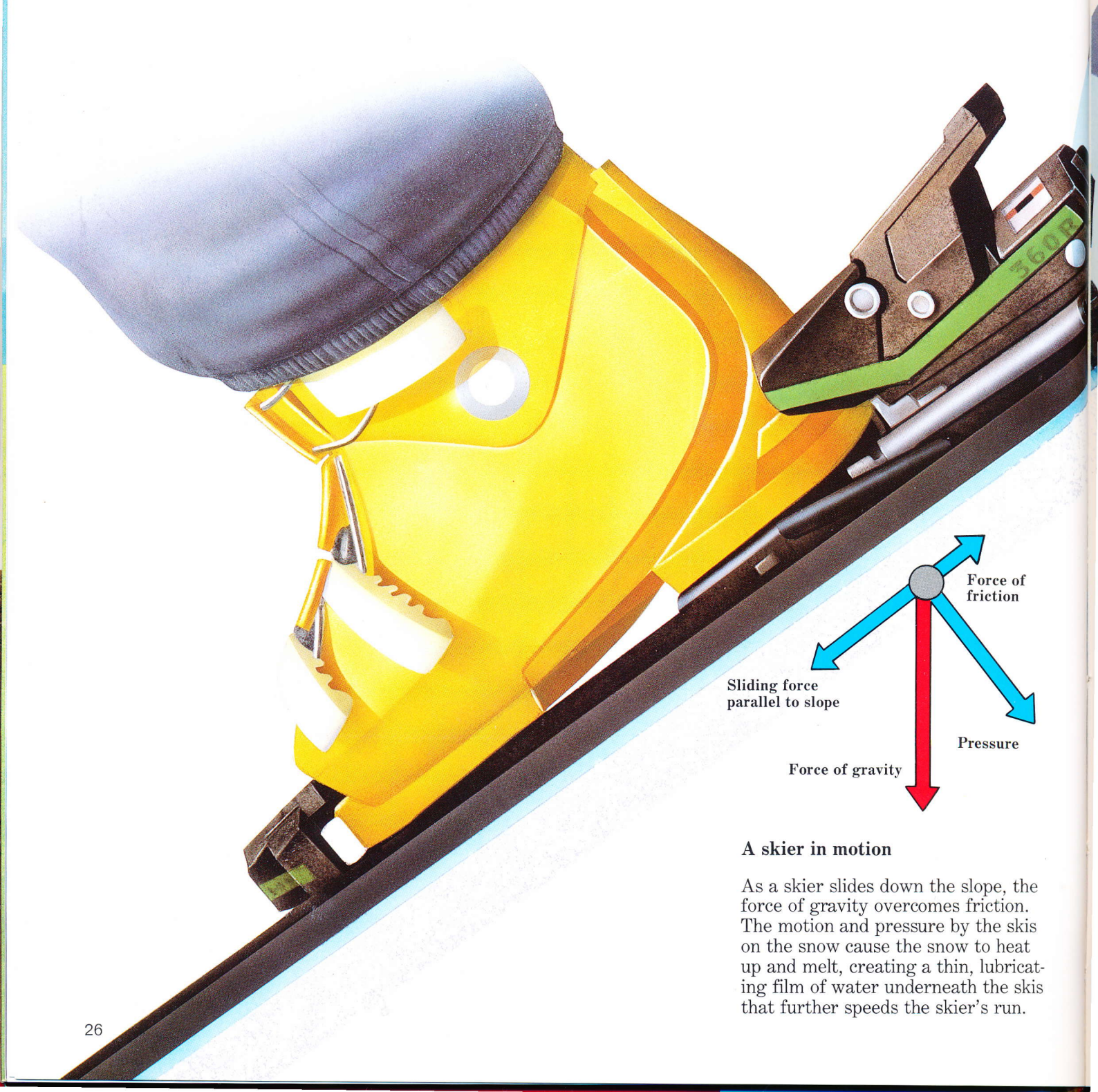
Governed by the laws of motion, rotating objects display unusual patterns like the curve of a thrown baseball and the wobble of a spinning top (*right*).



How can skiers move so quickly?

Skiers can race downhill—often at more than 160 kilometres per hour—because they are able to overcome friction, the force that prevents sliding between two objects. When a skier first steps onto a slope, friction causes the skis to stick to the snow. But the skier's weight exerts a force perpendicular to the slope that melts a thin layer of snow under the skis, creating a film of water. This film acts as a lubricant, greatly reducing the braking force of friction and allowing the force of gravity to pull the skier down the slope. As the skier moves forward, heat generated by the skis sliding against the snow continuously melts new snow underneath the skis, maintaining the watery film. A skier can gain even more speed by coating the bottoms of the skis with wax, which repels water and further reduces friction.

For the same reason, ice-skaters glide over a thin film of water, rather than on the ice itself. The great pressure that is exerted by the skates' narrow blades causes the ice to melt, nearly eliminating friction.



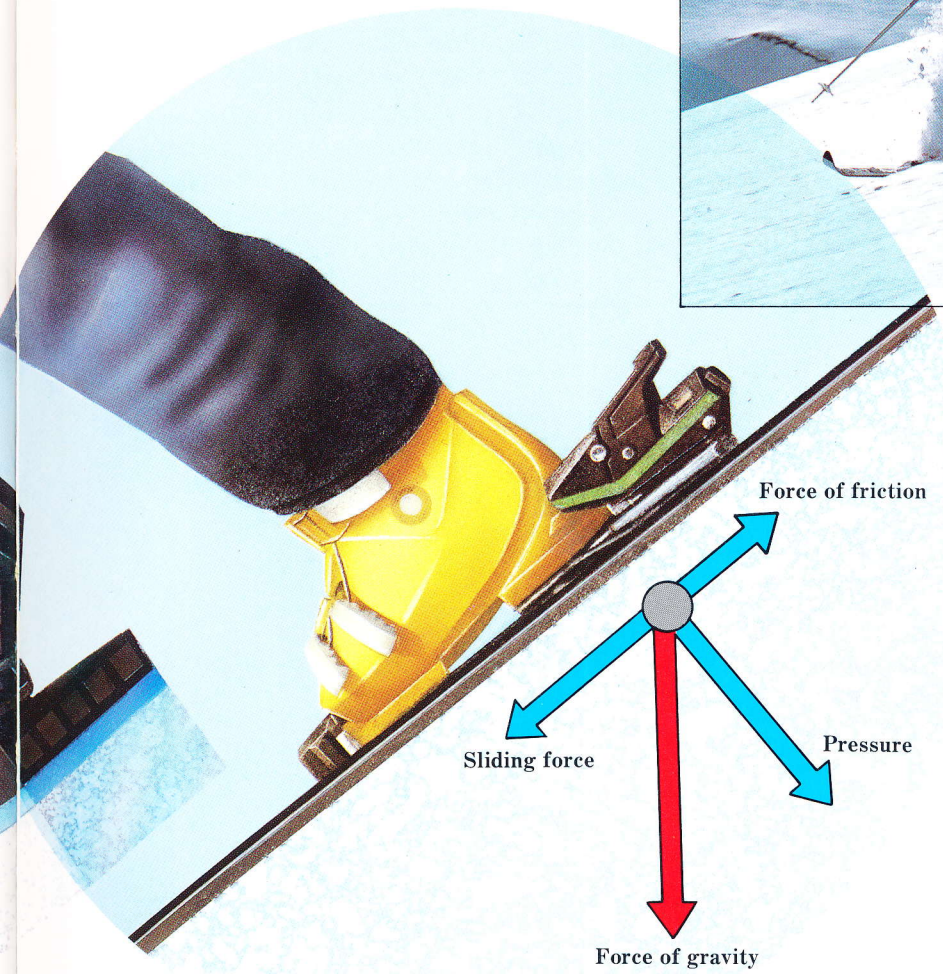
A skier in motion

As a skier slides down the slope, the force of gravity overcomes friction. The motion and pressure by the skis on the snow cause the snow to heat up and melt, creating a thin, lubricating film of water underneath the skis that further speeds the skier's run.

A skier starting out

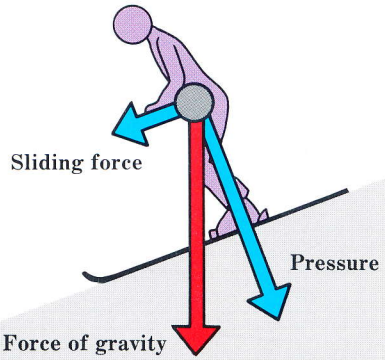
At first, the force of friction between the skis and the snow presents a barrier to a skier's downward motion. But once the skier's weight exerts pressure on the snow, the snow begins to melt and the skier glides down.

A woman on a downhill run



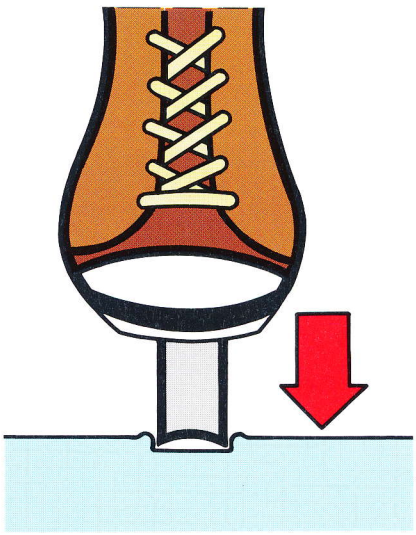
The forces acting on a skier

For a skier on a slope, the force of gravity has two components: One is perpendicular to the slope and pushes down on the snow; one is parallel to the slope, causing the skier to move downhill.



Skating on ice

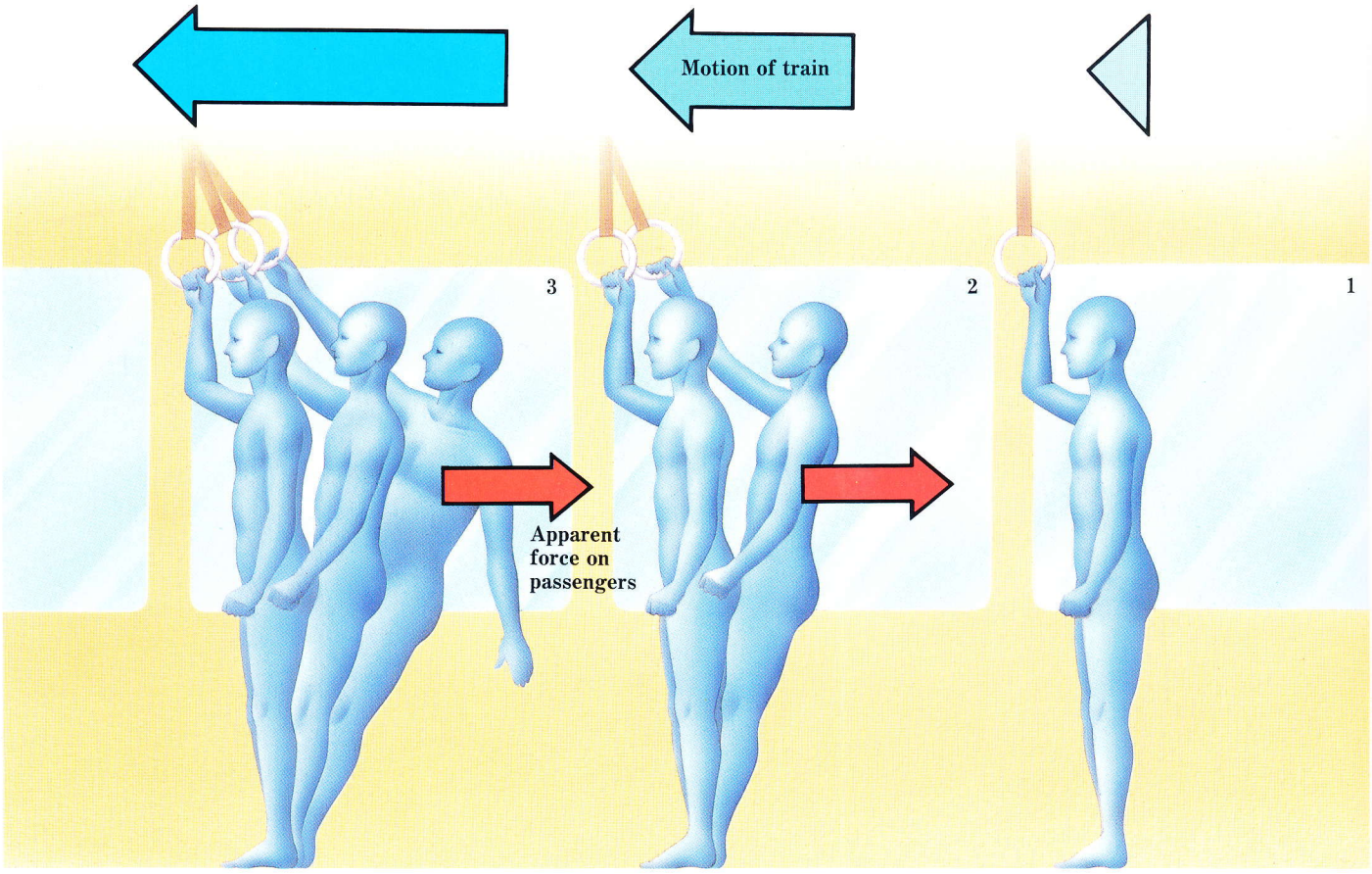
Like skiers, ice-skaters move on a layer of water between the ice and the skates. The enormous pressure of the blades on the ice lowers the freezing point of the ice enough so that the surface of the ice begins to melt. The more the pressure increases, the more the ice will melt and the faster the skater will glide along.



What is inertia?

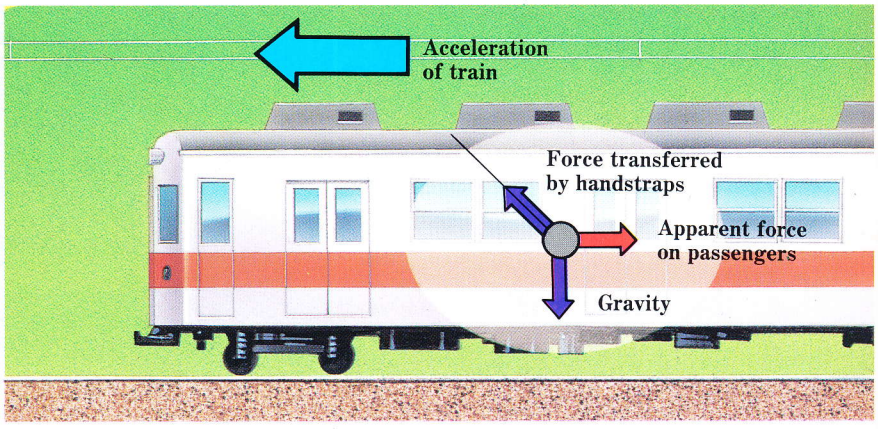
Objects do not move on their own unless a force sets them in motion or changes their direction. The resistance to change is called inertia, which means simply that bodies at rest remain at rest, and moving bodies remain in motion unless acted on by outside forces. When an electric fan is turned off, for example, the rapidly spinning blades continue to turn for a while before slowing down and stopping. Were it not for the friction between the blades and the motor, and air resistance, the blades would spin indefinitely even though the fan was off. But once the blades have stopped spinning, they will not start again on their own. A force, in this case an electric motor, is necessary to start the fan. The tendency of all objects to retain their state of motion—whether stationary or moving—explains why passengers standing on a train fall backward or forward when the train starts or stops (*below*).

Ever since the Greek philosopher Aristotle investigated inertia more than 2,000 years ago, many great thinkers have puzzled over the concept. In 1635, Italian physicist Galileo Galilei performed a series of experiments using balls rolling down inclines that led him to the first modern description of inertia. Building on Galileo's work, Sir Isaac Newton summed up his findings on inertia as the first of his three laws of motion.



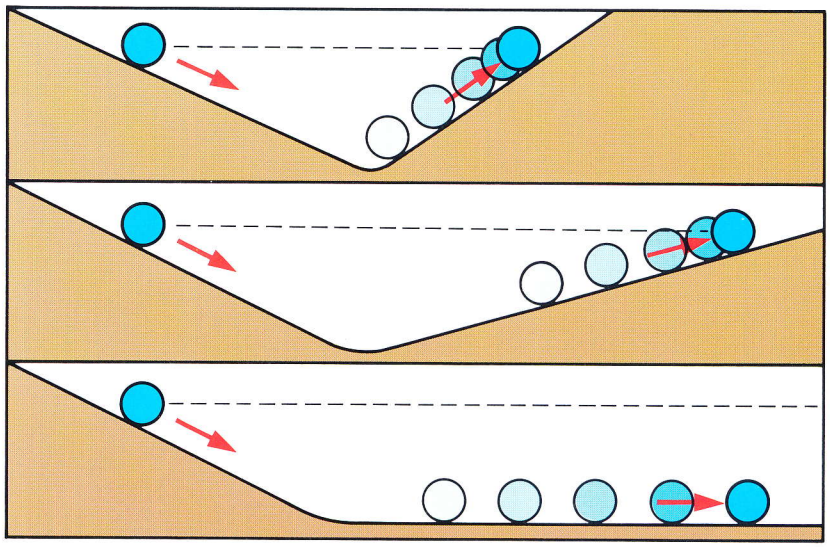
Bodies at rest

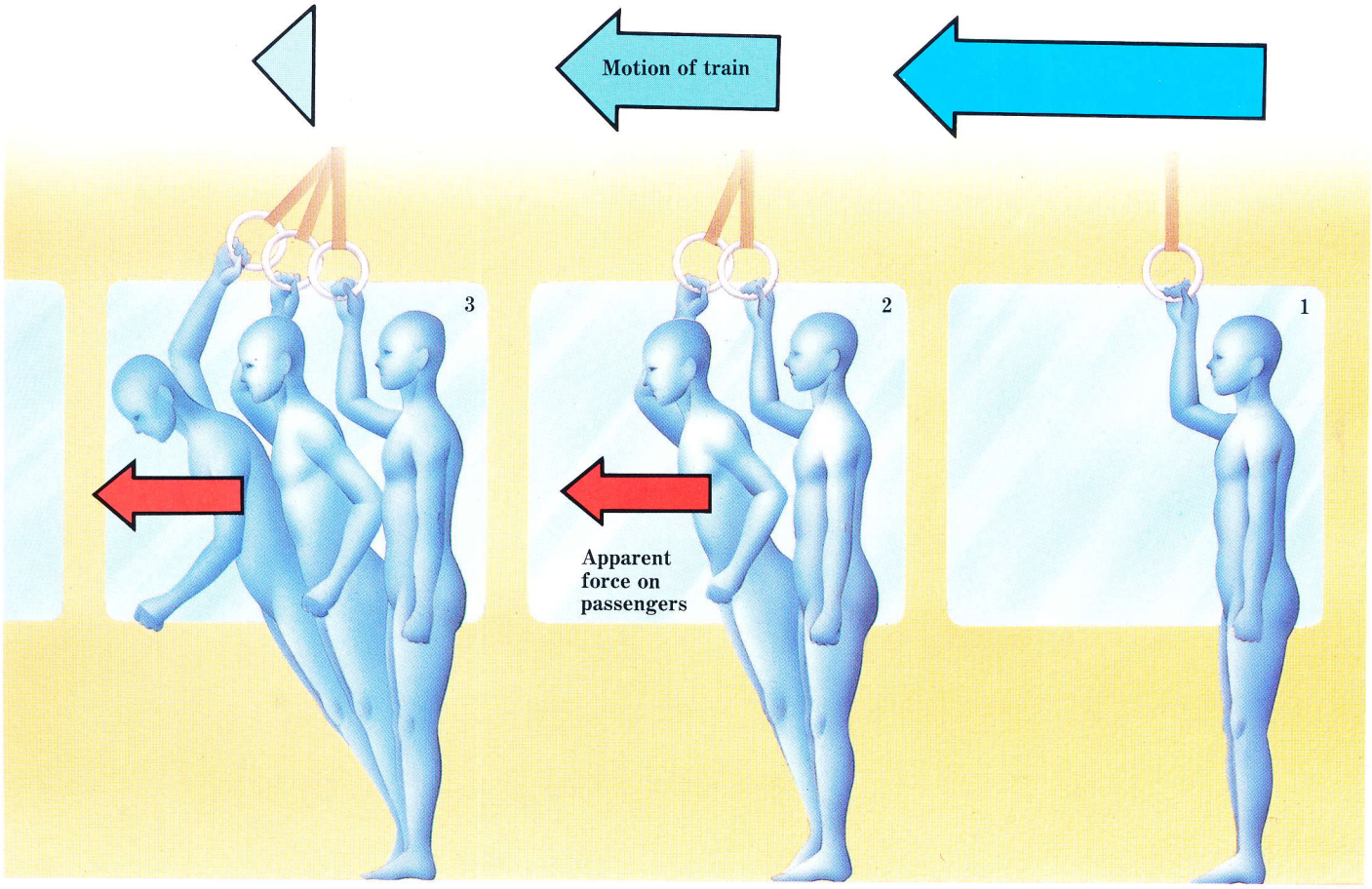
As shown in the illustration above, passengers are caught unawares when the train starts to move, and they begin to fall backward. The diagram at right shows how the handstrap carries, or transfers, the force that is needed to shift the riders forward, while gravity holds them in place. The passengers react to the acceleration as if an invisible force is pulling them backward.



Galileo's experiment

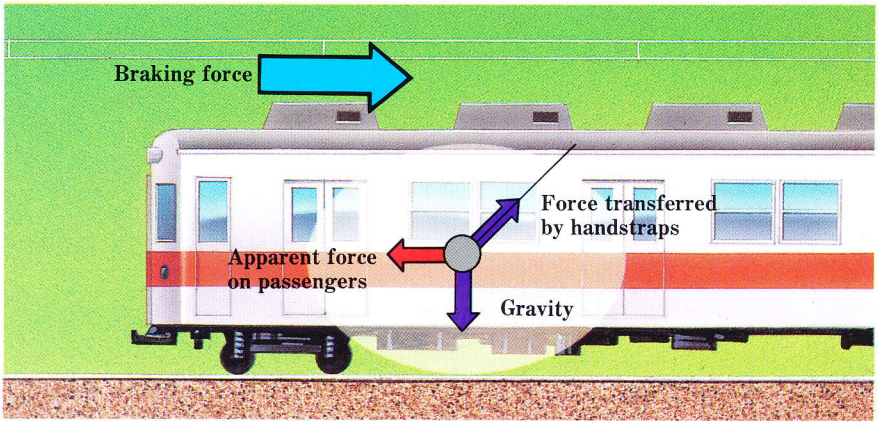
Through his observations of balls rolled along inclined planes, Galileo was able to describe inertia correctly. If there were no friction to slow things down, a ball rolled down an incline would continue to roll up a second incline (*top*) until the force of gravity overcame its kinetic energy, or energy of motion. In the middle example, the ball travels farther along the second incline than in the top example, since the second incline is not as steep. Galileo reasoned that as the angle of the second incline decreased, the ball would roll farther before giving in to gravity. If the second plane were horizontal, as in the bottom example, gravity would not affect motion, and the ball would roll forever.





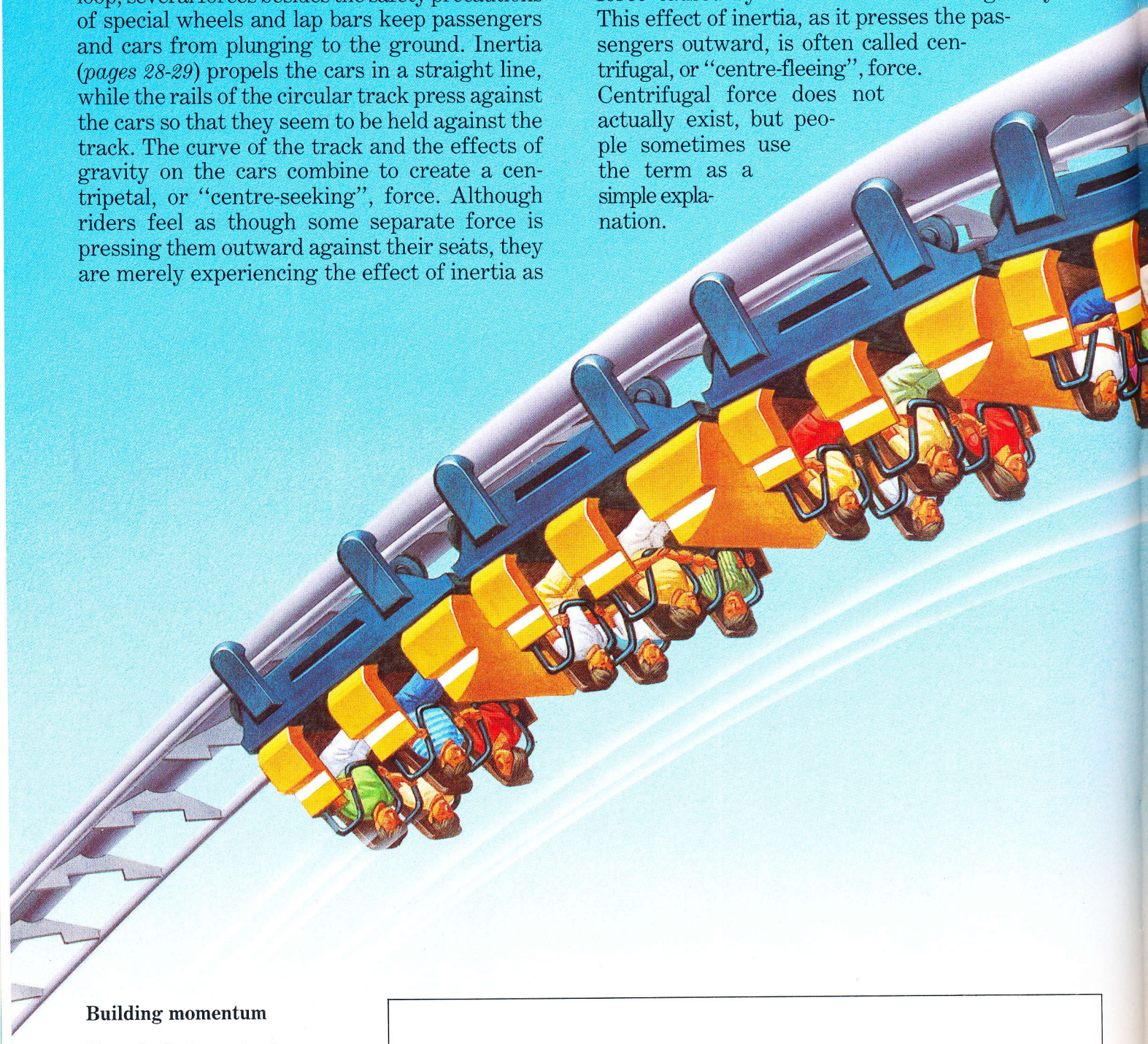
Bodies in motion

As a moving train slows down, its brakes exert a force opposite to the direction of motion (*blue arrow*) to stop it. Since no similar braking force acts on passengers standing inside the train, they keep moving and fall forward. The force transferred through the handstrap and the force of gravity transmit the stopping force from the train to the passengers. The abrupt change in motion makes the riders feel as though a force pushed them forward.



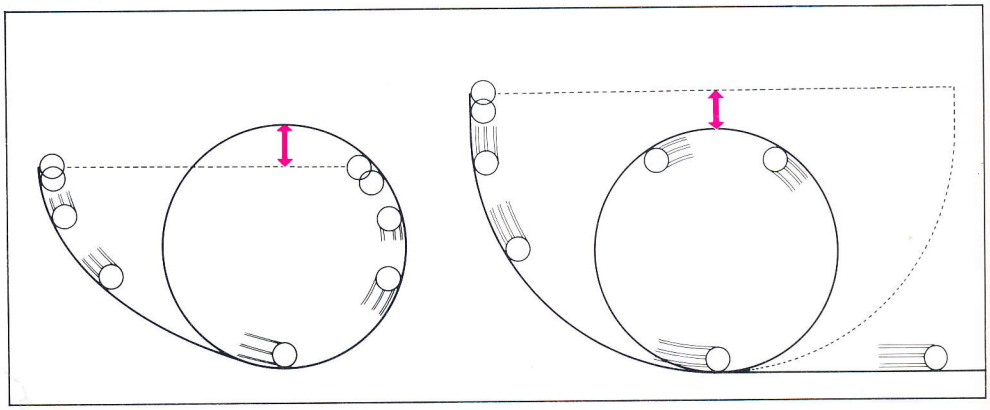
Why don't people fall out of an upside-down roller coaster?

When a hurtling roller coaster enters a loop-the-loop, several forces besides the safety precautions of special wheels and lap bars keep passengers and cars from plunging to the ground. Inertia (*pages 28-29*) propels the cars in a straight line, while the rails of the circular track press against the cars so that they seem to be held against the track. The curve of the track and the effects of gravity on the cars combine to create a centripetal, or "centre-seeking", force. Although riders feel as though some separate force is pressing them outward against their seats, they are merely experiencing the effect of inertia as it works against and balances the centripetal force caused by the curved rails and gravity. This effect of inertia, as it presses the passengers outward, is often called centrifugal, or "centre-fleeing", force. Centrifugal force does not actually exist, but people sometimes use the term as a simple explanation.



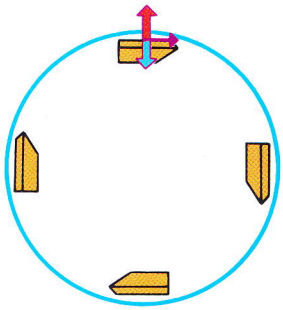
Building momentum

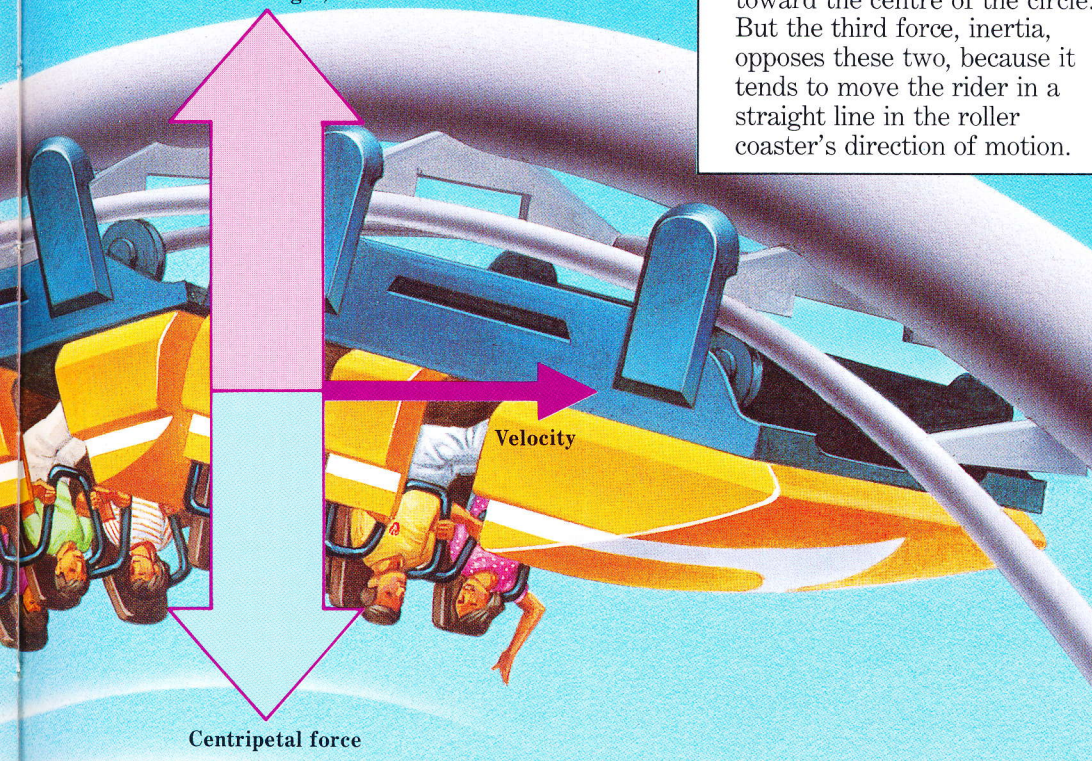
To make it through a loop, a car must have a lot of momentum—a product of its mass and speed. If the momentum is too small, the so-called centrifugal force will not exceed the force of gravity and the car will fall off. But if the launching hill is high and steep enough, the cars will have enough momentum to roll through and out of the loop.



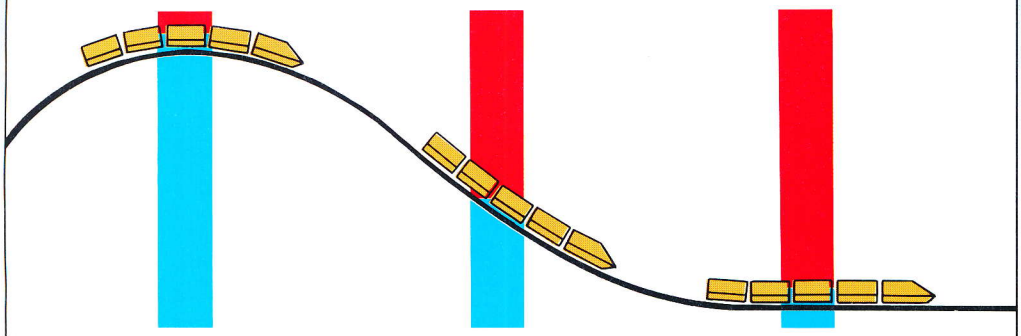
A combination of forces

Several forces act on the rider at the top of a loop. Gravity pulls the rider down. Pressure from the seat pushes the rider toward the centre of the circle. But the third force, inertia, opposes these two, because it tends to move the rider in a straight line in the roller coaster's direction of motion.





Potential and kinetic energy



Cars starting on a hill have great potential energy (*blue*) but little kinetic energy, or energy of motion (*red*).

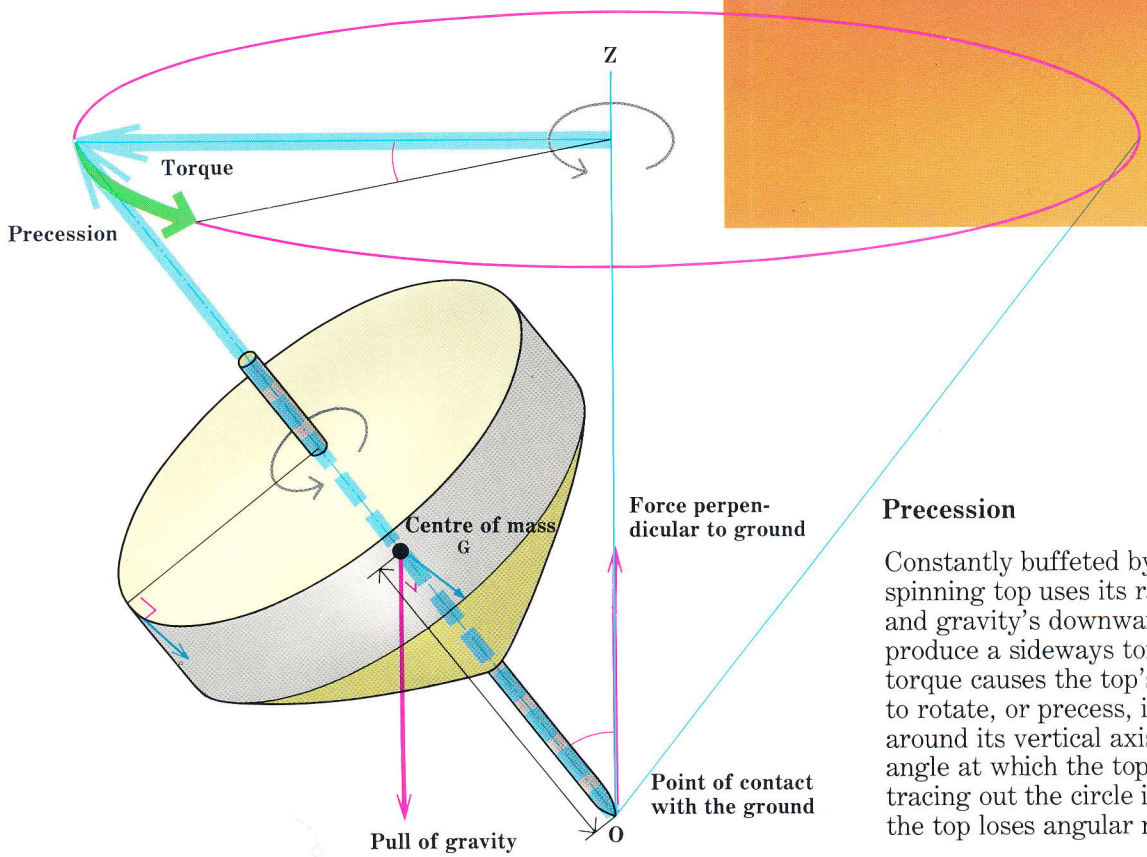
As the roller-coaster cars gather speed in their descent, their potential energy is changed into kinetic energy.

At the bottom of the ride, nearly all the potential energy (*blue*) has been transformed into kinetic energy (*red*).

How can a spinning top stay upright?

Although a stationary top cannot be balanced on its end, a spinning top can stay upright for minutes. A spinning top, as well as all other rotating bodies, possesses a property called angular momentum—the product of the top's distribution of mass and its rate of spin—that produces a rotating force. Called a torque, this force causes the top's spin axis to rotate rather than fall over and produces the familiar wobble, technically known as precession. As friction between the ground and the top makes the top lose some of its angular momentum, the top begins to slow down and fall.

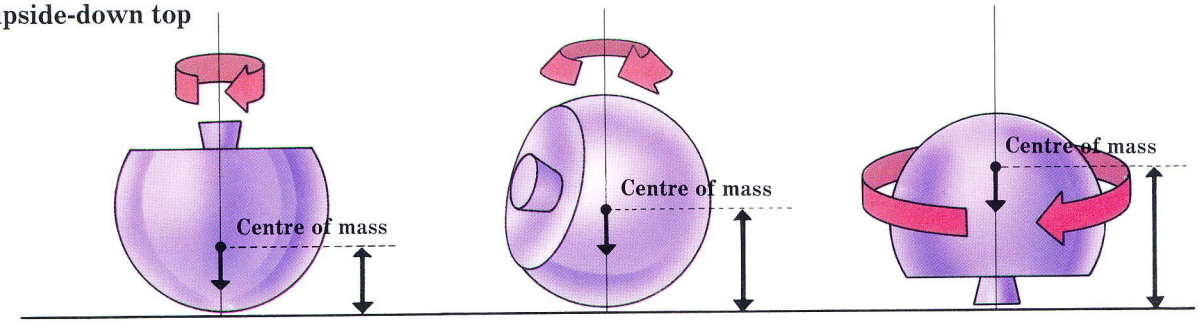
While spinning tops are fun to play with, their properties serve far more useful functions elsewhere. Their most important application lies in the gyroscope, which is little more than a top mounted on a pivoting cradle. Extremely sensitive to changes in direction, which affect its precession, the gyroscope is essential to the navigational systems of planes and boats, and has made possible the remote-controlled guidance of spacecraft.



Precession

Constantly buffeted by gravity, a spinning top uses its rate of spin and gravity's downward pull to produce a sideways torque. This torque causes the top's spin axis to rotate, or precess, in a circle around its vertical axis (O/Z). The angle at which the top leans while tracing out the circle increases as the top loses angular momentum.

The upside-down top



An upside-down top will turn over and begin spinning on its handle (*above, right*). The secret to this trick lies in its centre of gravity. Spinning tops are most stable when their centres of gravity lie high off the ground. When this kind of top begins to spin (*above, left*), its gravitational centre is near the ground. The centre of gravity is raised when the top spins on its side and then upside down, gaining far more stability. This action converts some of its kinetic energy into potential energy.

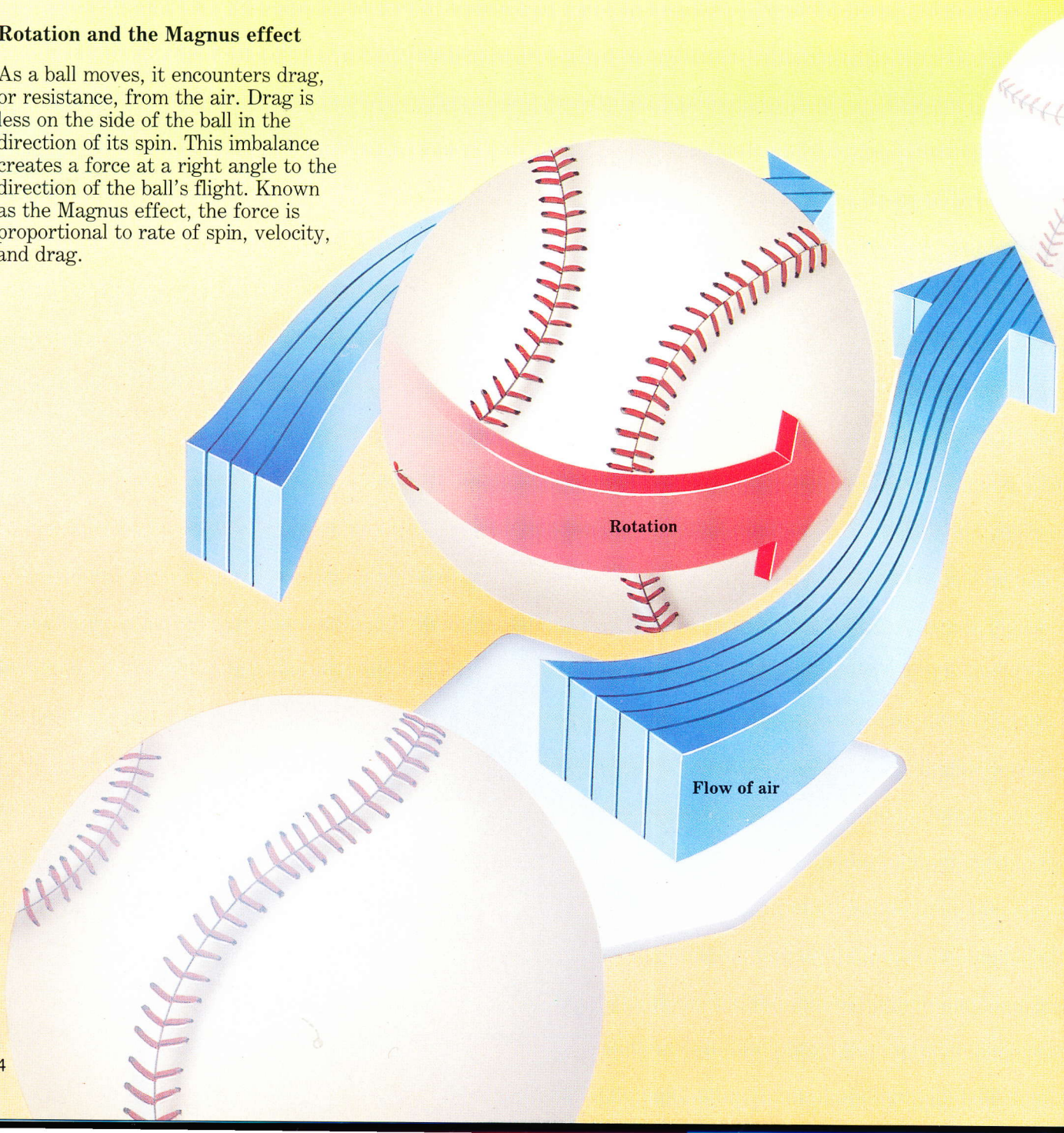
Why does a baseball curve?

People sometimes say that baseballs do not really curve, and that it is just an optical illusion. Baseball players and scientists know better. A first-class pitcher can make a ball curve, drop, or hop as it flies toward its target. The trajectory of a pitch is determined by the speed and direction of the spin imparted to the ball as it leaves the pitcher's hand. According to the laws of physics, any object, such as a baseball moving through air, is subject to a variety of physical forces, which combine to affect the course of the object's motion.

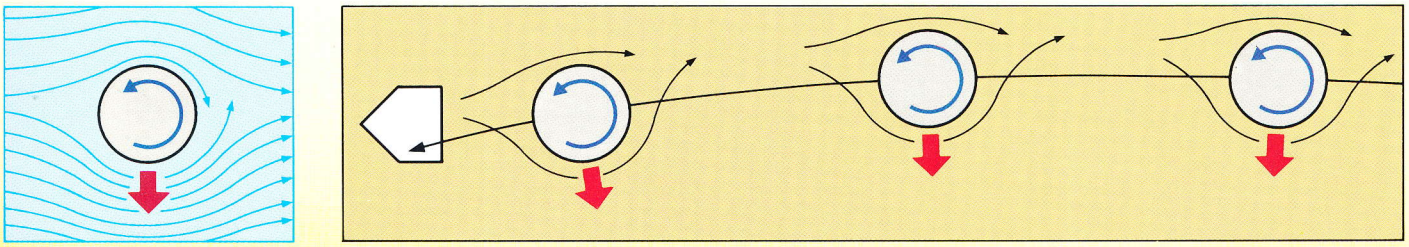
A baseball is sewn together with 216 stitches of red thread. Once the ball is in flight, the stitches carry a layer of air with them as the ball rotates. The air travels slightly faster on the side of the ball in the direction of the spin. The more rapidly air moves, the less pressure it exerts. Thus, air pressure is lower on the side of the ball in the direction of the spin and greater on the opposite side. Just as weather systems move from areas of high to low pressure, the baseball curves in the direction of its spin toward the low-pressure area. An expertly thrown curveball rotates about 18 times during its half-second flight to the target and its path may curve by as much as 44½ centimetres.

Rotation and the Magnus effect

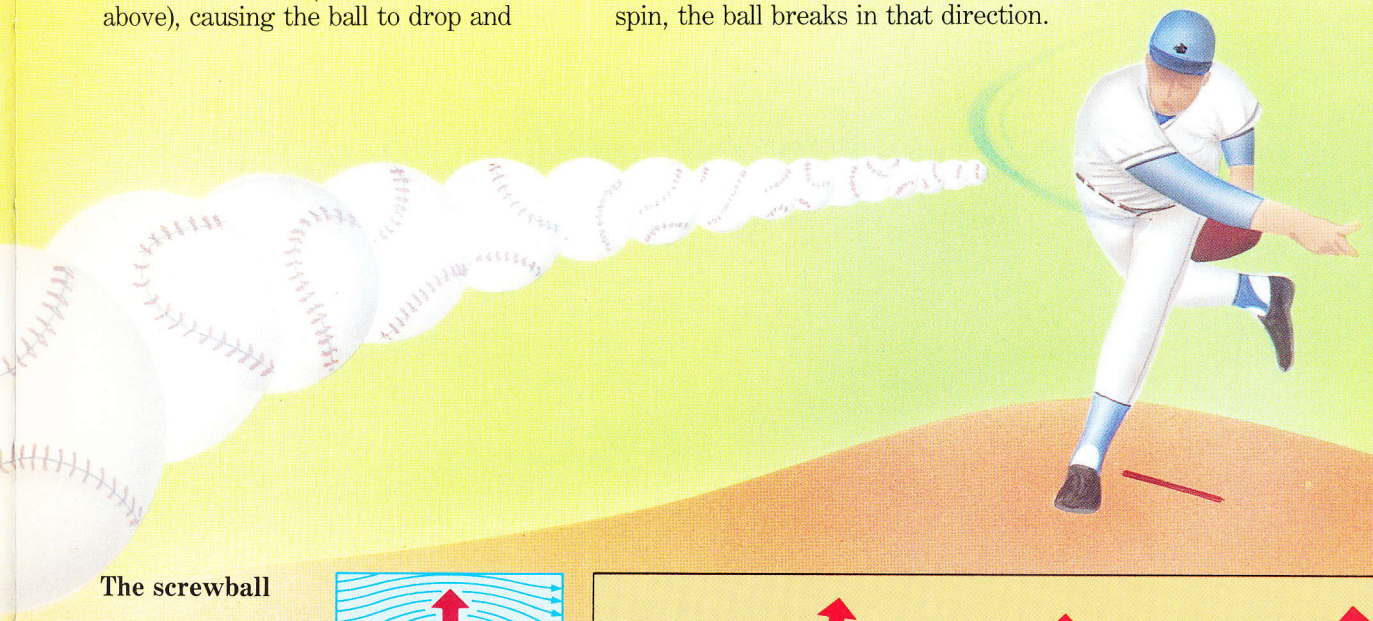
As a ball moves, it encounters drag, or resistance, from the air. Drag is less on the side of the ball in the direction of its spin. This imbalance creates a force at a right angle to the direction of the ball's flight. Known as the Magnus effect, the force is proportional to rate of spin, velocity, and drag.



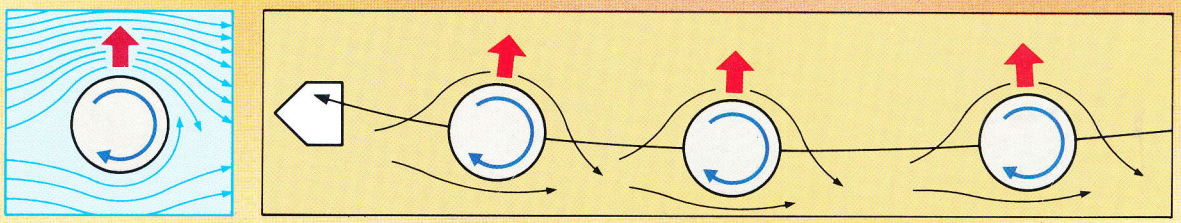
The curveball



A pitcher throws a curveball by twisting his wrist to make the ball spin. A right-hander's curve spins downward and anticlockwise (as seen from above), causing the ball to drop and resulting in a movement, or break, toward the right side of its destination. As the flow of air is faster on the side of the ball in the direction of the spin, the ball breaks in that direction.

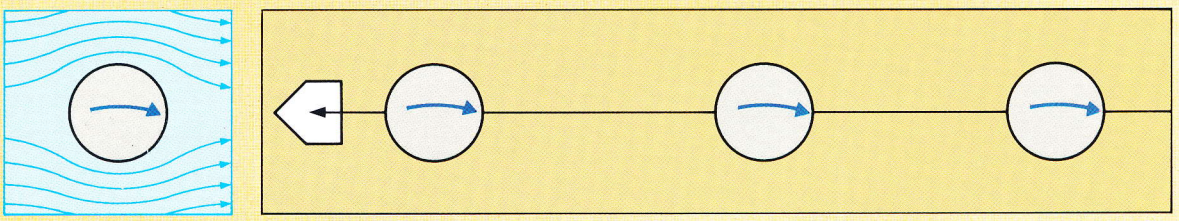


The screwball



A screwball is thrown by twisting the wrist toward the body, instead of away from the body as in a curveball. This twist gives the ball the opposite spin from a curve and causes it to break in the reverse direction. A right-hander's screwball breaks toward a right-handed batter.

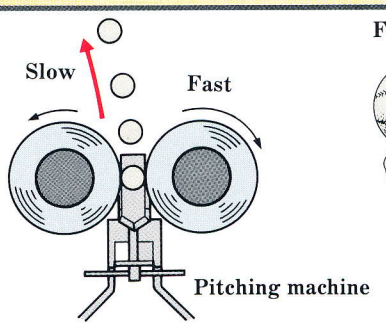
The fastball



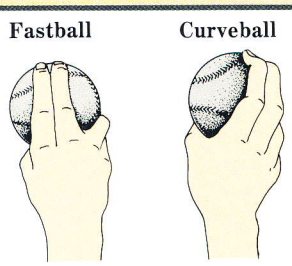
A good fastball is not simply a straight pitch; it also has its own special movement. At the point of release, the pitcher pulls downward on the seams, causing the ball to rotate backward toward the pitcher. This results in a Magnus effect directed upward and causes the ball to hop. A 145-kilometre-per-hour fastball may hop as much as 10 centimetres.

Putting spin on the ball

The difference between a fastball, curveball, and screwball is in the speed and direction of the ball's spin. The Magnus effect causes a ball to break in the direction in which it is spinning. A pitching machine creates differing spins by varying the speeds of the two ejector wheels. A pitcher does it by changing his grip on the ball.

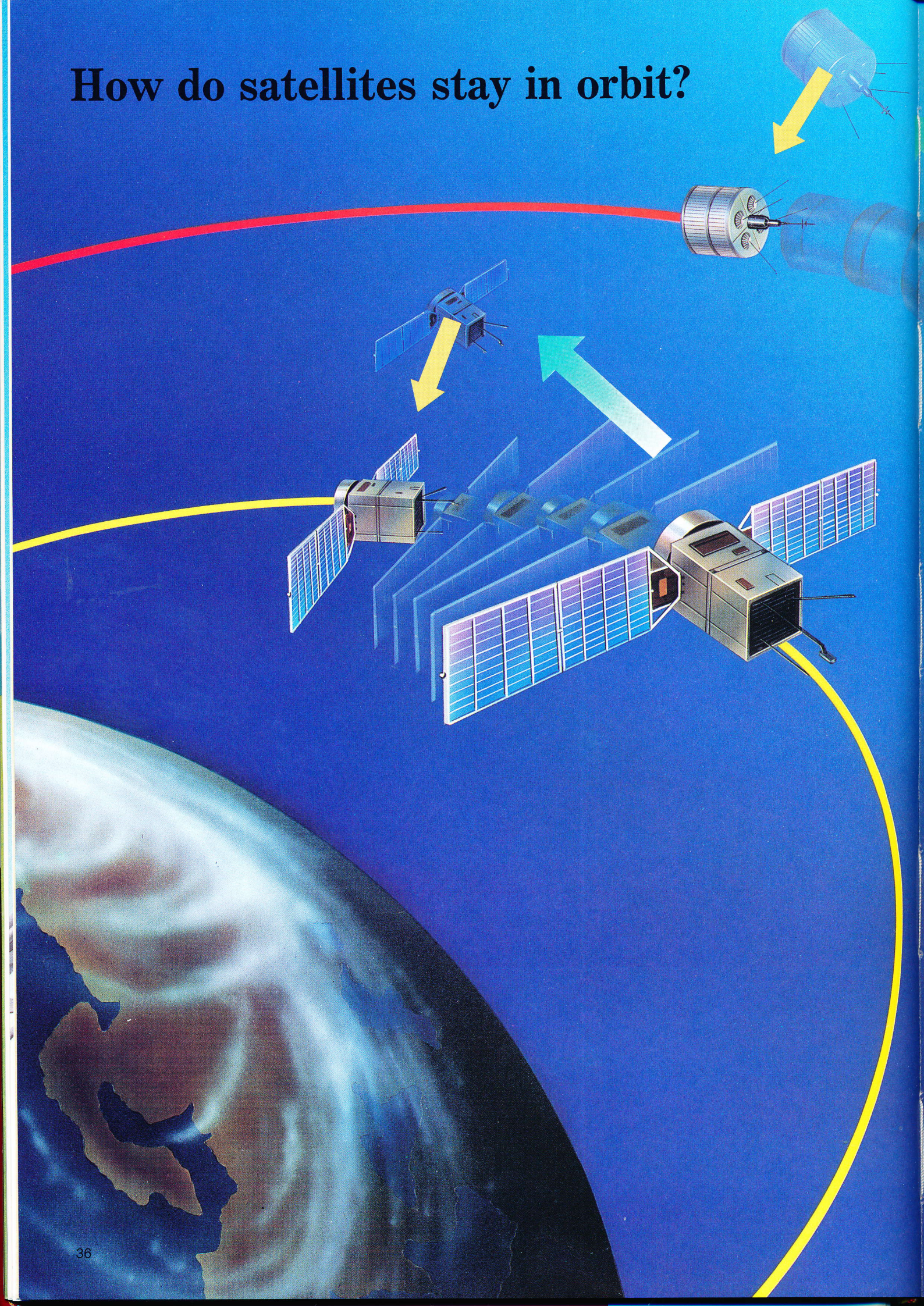


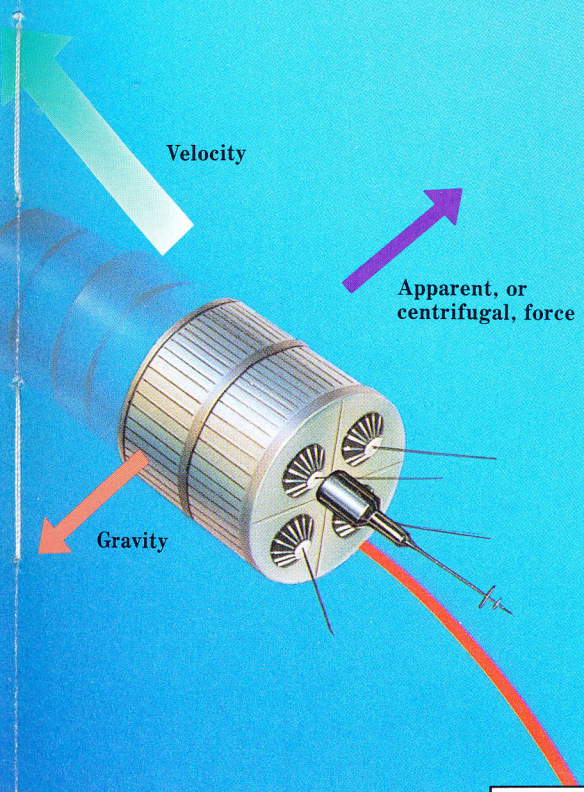
Pitching machine



Gripping the ball

How do satellites stay in orbit?





A satellite's orbit represents a delicate balance between inertia and gravity. The force of gravity is continuously pulling the satellite toward Earth, while the satellite's inertia keeps it moving in a straight line. If it were not for gravity, the satellite's inertia would send it straight out of Earth's orbit and into space. But at every point in the orbit, gravity reins in the satellite.

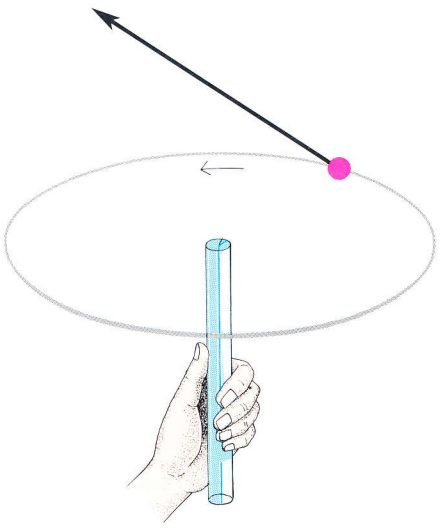
To reach a balance between inertia and gravity, the satellite must be moving at a precise speed. If it moves too fast, inertia overcomes gravity and the satellite leaves orbit. (The calculation of the speed that would propel a satellite out of Earth's orbit, that is, the escape velocity, plays an important role in the launching of space probes.) If the satellite moves too slowly, gravity wins its battle with inertia and the satellite plummets to Earth. That is just what happened in 1979, when the American space station Skylab began slowing down as a result of drag from the outer fringes of Earth's atmosphere. Gravity's unyielding grip then brought the spacecraft crashing down to Earth.

Speed and distance

Since the pull of gravity lessens with distance, the velocity needed to keep a satellite in orbit varies with altitude. Engineers can calculate how fast and how high a satellite must orbit. For example, a geostationary satellite—one that always remains over the same point on Earth—must circle the planet once every 24 hours, matching Earth's rotation, at an altitude of 35,900 kilometres.

Gravity and inertia

The balancing act a satellite performs with gravity and inertia can be mimicked by swinging a weight tied to a string. The weight's inertia pulls it constantly outward, while the tension in the string—playing the role of gravity—keeps the weight in a circular orbit. If the string were cut, the weight would fly off in a straight path perpendicular to the radius of its orbit.



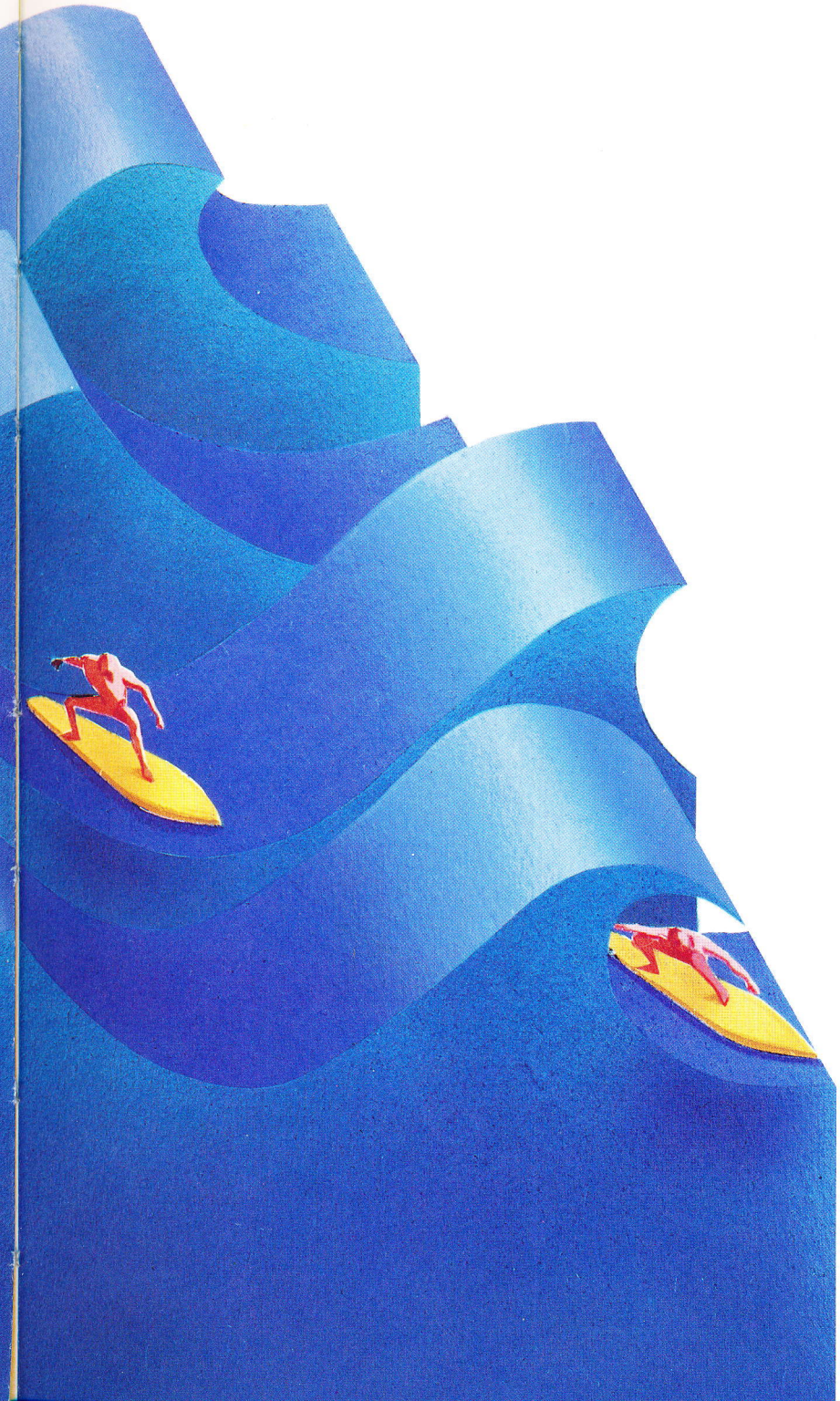
How can surfers ride waves?

The apparent effortlessness with which experienced surfers race over waves belies the complexity of the forces that make surfing possible. Waves vary in shape tremendously between their point of origin and the shore, and it is only close to the beach, where rising swells approach their first break, that surfers can ride them.

Generated by ocean currents, wind, and the moon's tidal pull, waves begin their lives in the deep ocean, far from any beach. As they move toward shore, they slow down and bunch up, becoming taller and narrower (*below, right*). Surfers take advantage of this motion by catching a wave as it begins to break. Standing slightly to the rear of centre on their boards to balance their weight, and keeping the noses of the boards clear of the water, surfers manoeuvre their boards sideways across the wave. Each surfboard is thrust forward by a combination of the force of gravity, buoyancy, and the wave's forward motion. In essence, the board slides down the wave as it moves ashore.

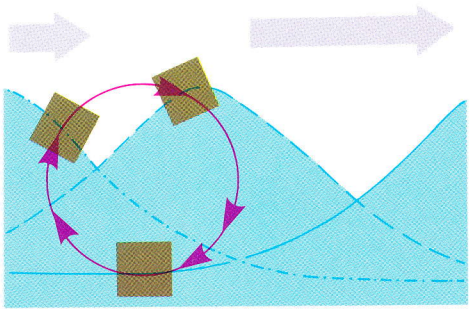
Catching a wave

When a surfer begins a ride, the wave is shallow and moves quickly to shore. But as the wave approaches the beach, it slows down and becomes steeper, challenging the surfer to maintain his balance as the wave crests.



Deep ocean waves

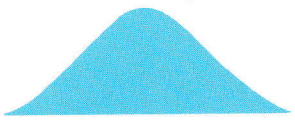
Waves far from shore are too shallow and too fast for surfing. As a wave approaches, an object such as the block of wood shown below is pushed up and slightly forward. But as the wave passes, the block slides back to the starting point.



A surfer slides down a breaking wave.

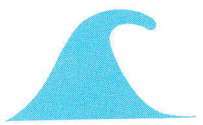
History of a wave

Wave on the open sea



When waves originate far out at sea, they are broad and symmetrically shaped, and move very quickly.

Wave nearing the beach



As waves approach the shallower bottom near the beach, they slow down and bunch up, toppling over themselves.

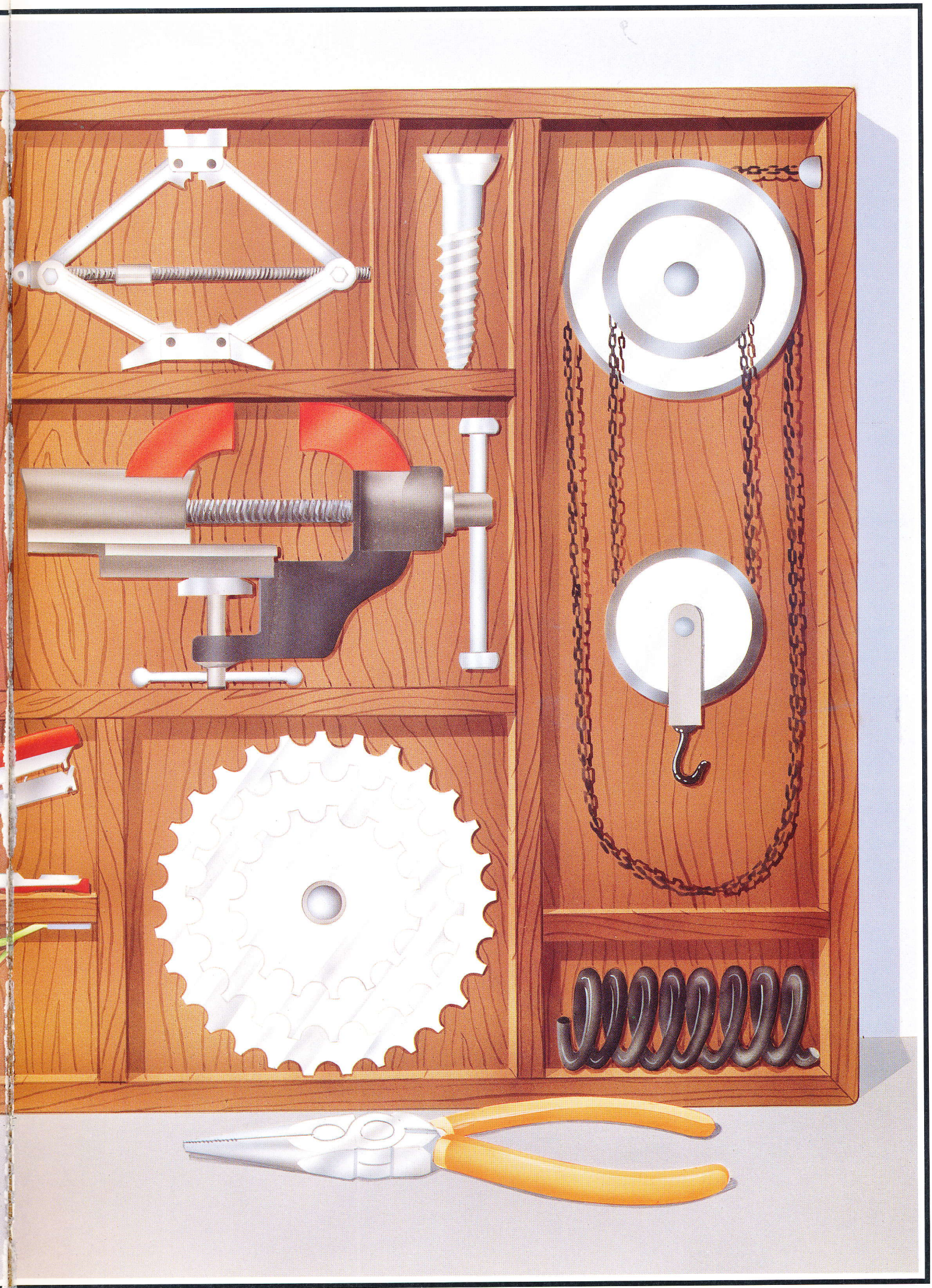
3
Simple machines

Most modern machines, no matter how sophisticated, consist of combinations of a few basic moving parts. Called simple machines by physicists, these parts—the lever, the inclined plane, and the wheel—have served humans since the dawn of civilization. With the exception of electronic devices, today's highly complex mechanized marvels are direct descendants of tools used thousands of years ago to cut down trees, build shelters, and erect the great pyramids.

Physicists define the five types of simple machines as the lever, the wheel and axle, the pulley, the inclined plane, and the screw. Each works in one of three ways. It can take the force exerted by a person and redirect it, for example by allowing the person to pull on an object, rather than push. It can turn a small effort or force into a larger force, a concept known as mechanical advantage. Or it can magnify the distance over which a force acts. While these machines do not reduce the amount of work needed to perform a task, they do reduce the effort required from the user. With the proper simple machines, used either alone or in combination, even the most formidable of tasks can be made easier.

Springs are related to simple machines. Mechanical devices that stretch and compress consistently, springs can be used to measure the strength of forces.

From construction cranes to tin-openers to most of the tools shown at right, mechanical devices rely on just a few simple principles.

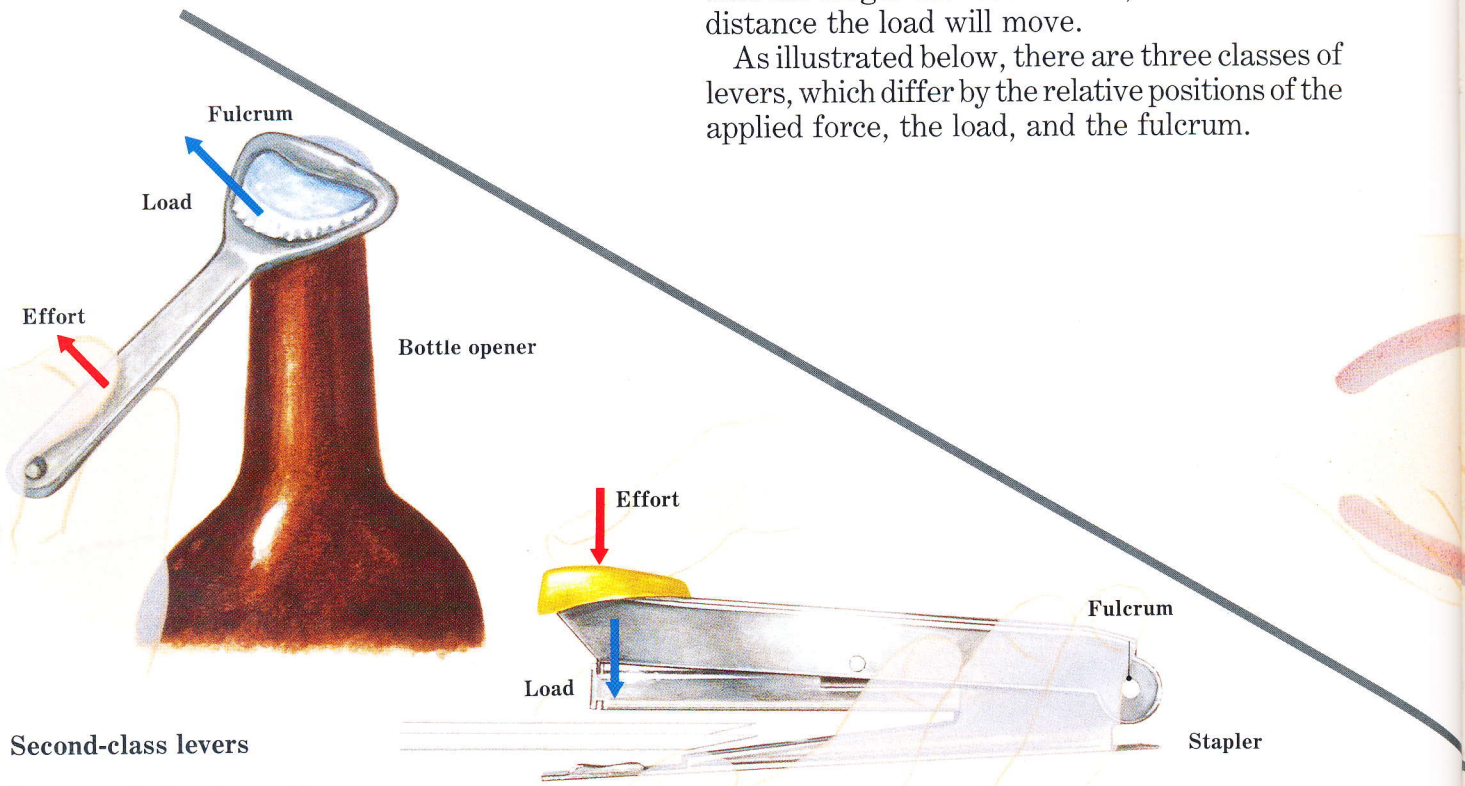


What are levers?

A lever is a narrow beam that rotates around a single point, called the fulcrum. By placing an object to be moved, called a load, at one point on the beam and applying an effort at another point, a person can move the object far more easily than by picking it up and moving it by hand.

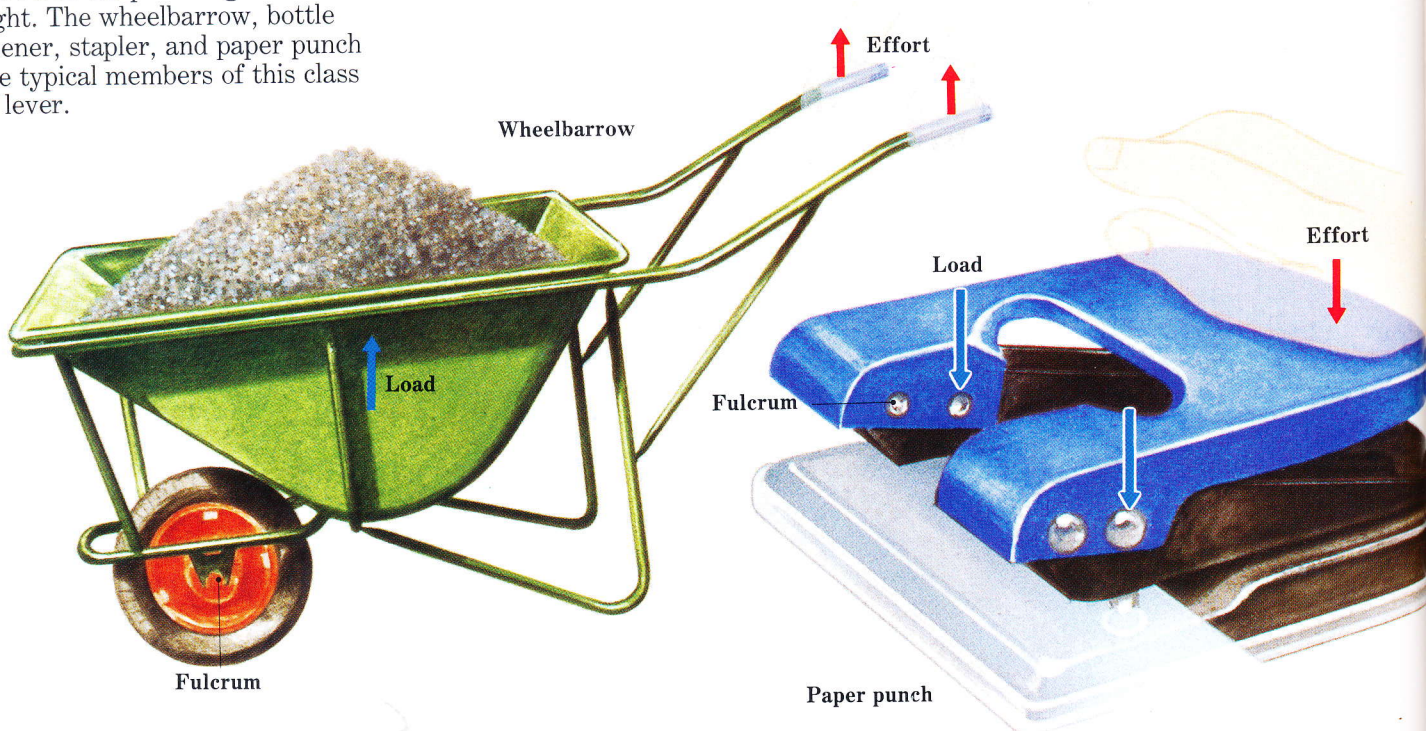
Levers work by a simple formula: The effort multiplied by its distance from the fulcrum equals the weight multiplied by its distance from the fulcrum. The longer the lever arm, the greater the force amplification, and the easier it becomes to move the load. The price for this advantage is that the longer the lever arm is, the shorter the distance the load will move.

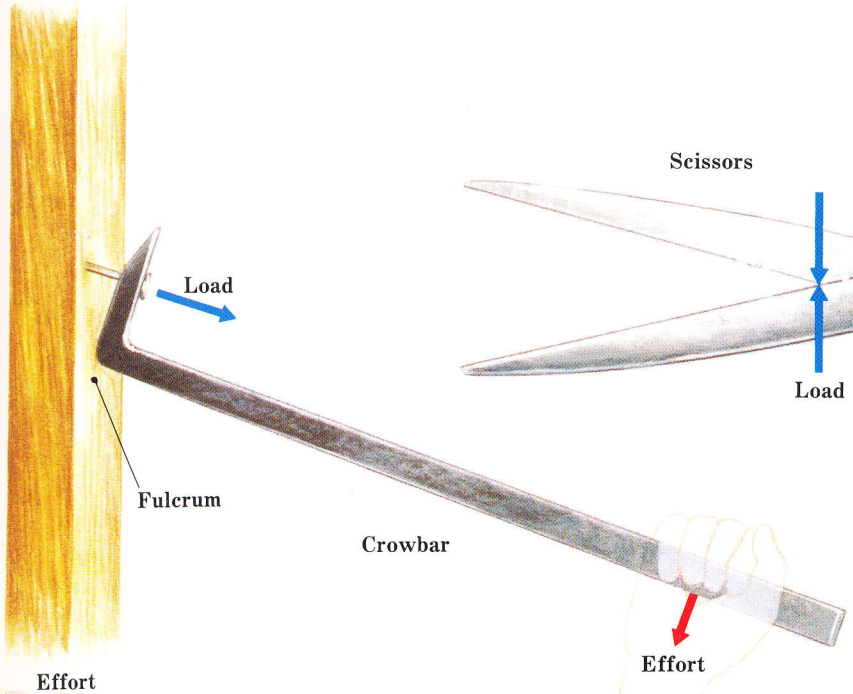
As illustrated below, there are three classes of levers, which differ by the relative positions of the applied force, the load, and the fulcrum.

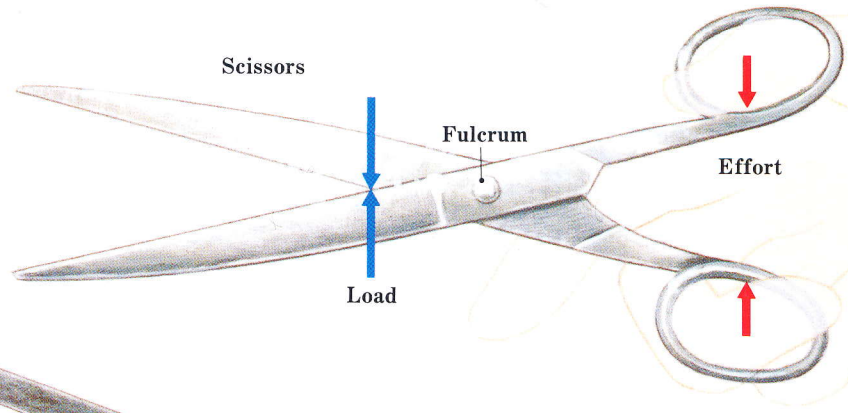


Second-class levers

In a second-class lever, the fulcrum lies at one end, an effort is applied at the other end, and the load (W) lies in between, as shown in the pink diagram at right. The wheelbarrow, bottle opener, stapler, and paper punch are typical members of this class of lever.

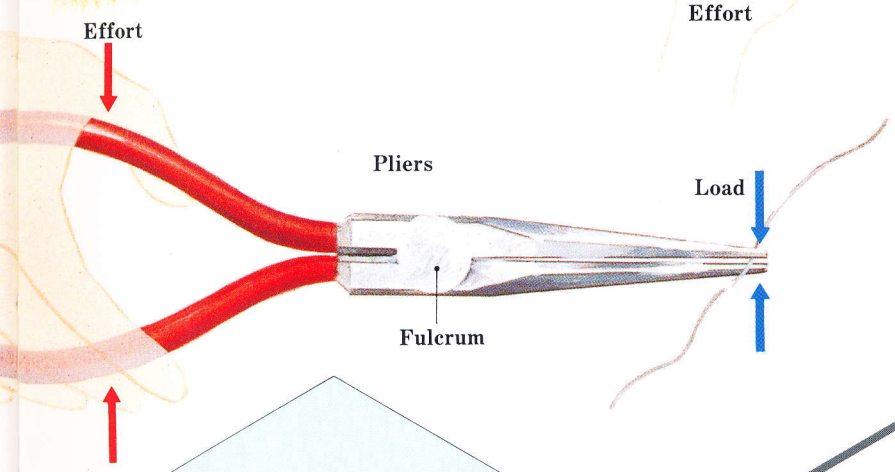


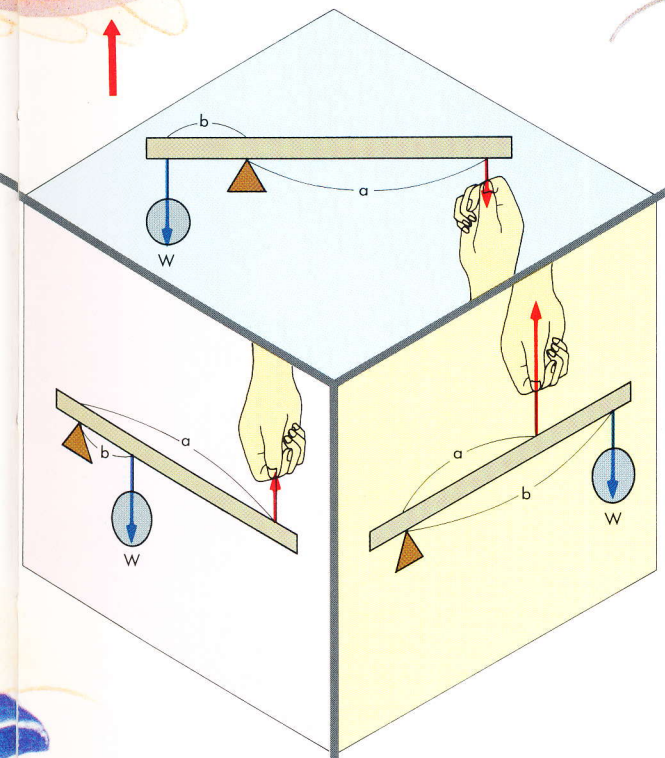




First-class levers

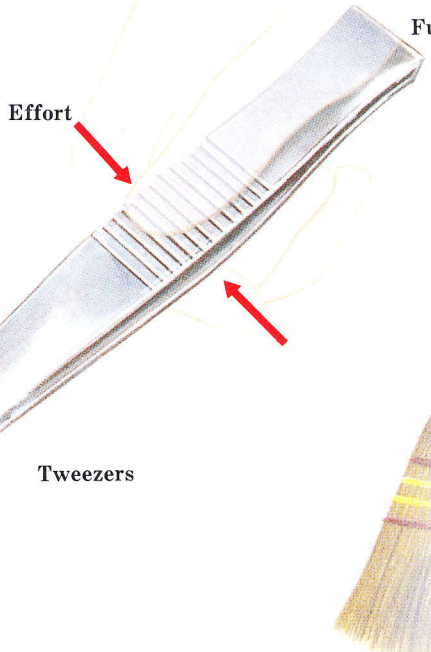
The most common type of lever is the first-class lever, in which the fulcrum lies between the load (W) and the applied effort (*blue diagram*). First-class levers take many forms, including the crowbar, scissors, and pliers shown at left.

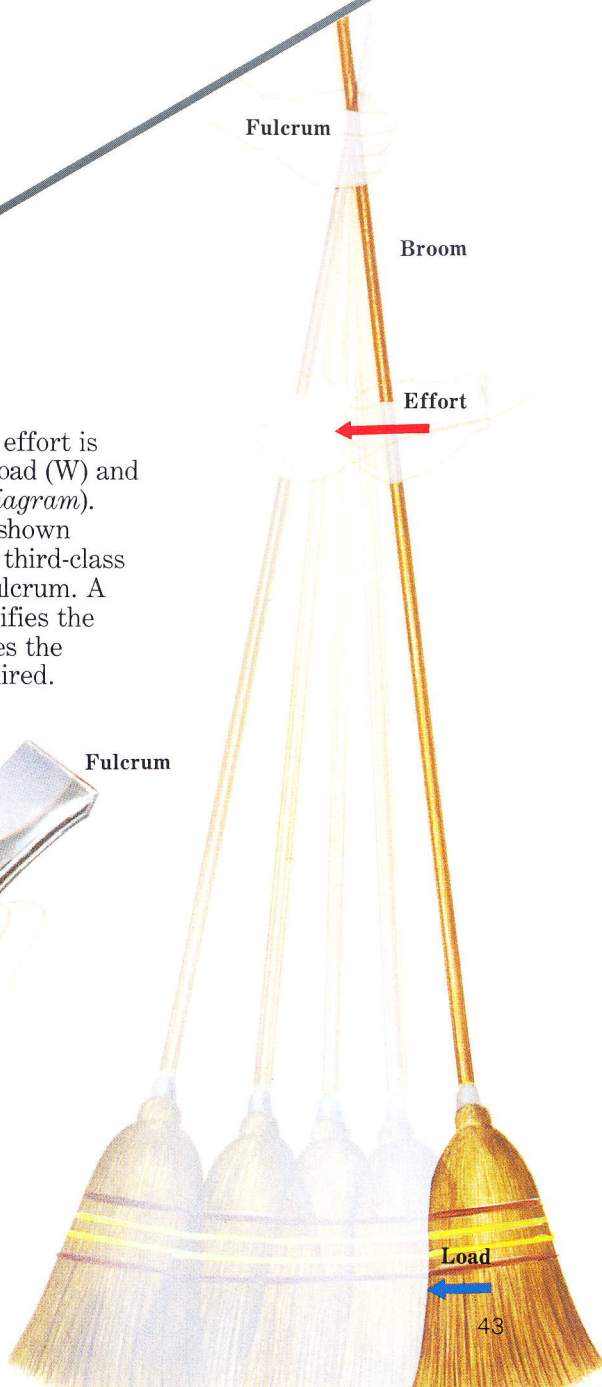




Third-class levers

In a third-class lever, effort is applied between the load (W) and the fulcrum (*yellow diagram*). The pair of tweezers shown below consists of two third-class levers joined at the fulcrum. A broom typically magnifies the distance and minimizes the amount of effort required.



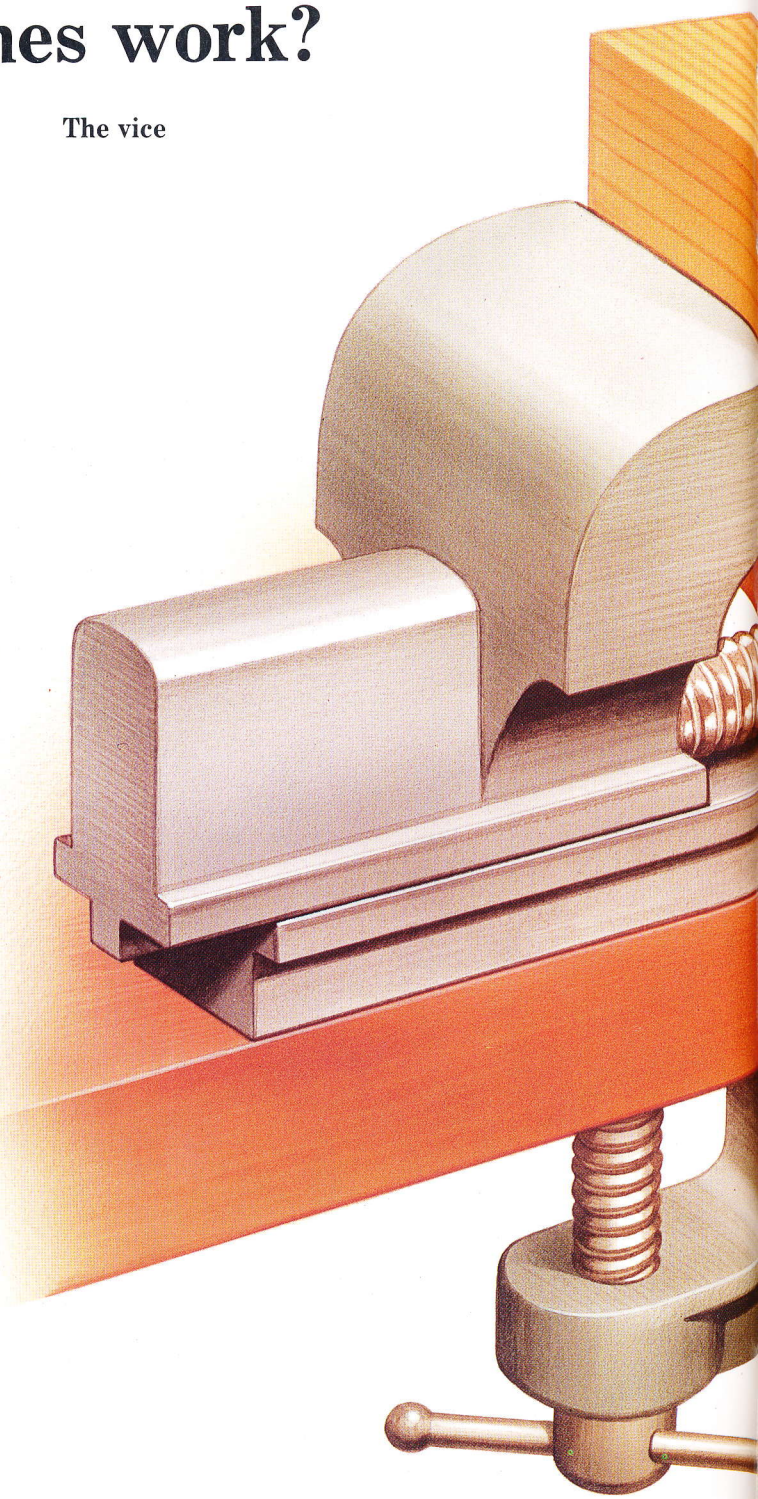


How do inclined planes work?

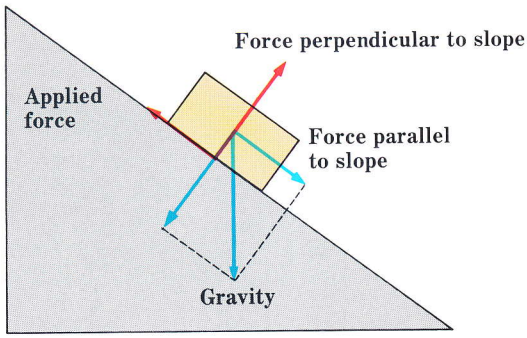
Like levers, inclined planes reduce the effort needed to raise an object. For example, a block weighing 50 kilograms would be difficult to lift, but it can easily be raised by sliding it up a ramp. Placing the block on a tilted surface divides its weight into two components, one parallel and one perpendicular to the surface. To move the block up the ramp, a person needs only to overcome the parallel component, the magnitude of which increases with the ramp's tilt.

Inclined planes take many forms. The screw, for example, consists of an inclined plane, which is the screw's thread, wrapped around a cylinder. When the screw is turned, the threads dig deeper into an object and hold tight by virtue of the great friction that exists between the object and the threads. The vice converts lever action and the screw's rotary motion into straight-line pressure, as does the screw of a car jack, which lifts objects by the same principle.

The vice



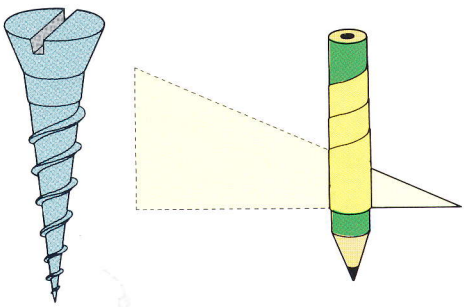
Forces on an inclined plane



For an object on an incline, gravity is exerted parallel and perpendicular to the plane. Pushing the object up the incline requires a force equal to that of the parallel component of gravity.

Planes and screws

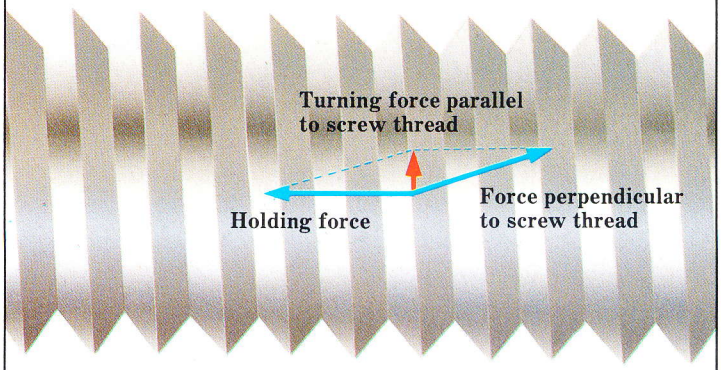
It is easy to see the screw's relation to the inclined plane by wrapping a paper triangle around a cylinder. The resulting spiral is identical to the pattern of threads on a screw.



Force and work. Although an inclined plane can make a task easier, it does not reduce the amount of work required for performing the task. Lifting a block of 50 kilograms (W) 7 metres straight up (*far right*) requires 50 x 7 metre-kilograms of work, that is, the block's weight times the distance it moves. When the block is placed on an incline of 44.5°, the force (F) needed to pull the block is reduced to 70 percent of the block's weight. While this makes the block easier to move, it must now be pulled along 10 metres of ramp to get it to a height of 7 metres. In other words, the mechanical advantage is the result of resistance, 7 metres, divided by effort, 10 metres.

Forces acting on a screw

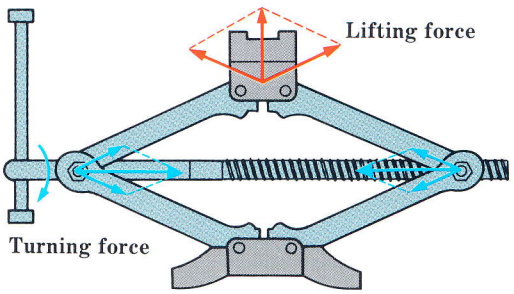
As a screw turns, its threads exert a powerful force on the material it pierces. This force acts to pull the screw forward if it is turning clockwise and backward if it is turning anticlockwise.



A vice combines the functions of the screw and the lever.

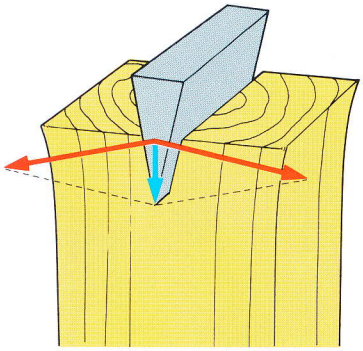
A screw for lifting

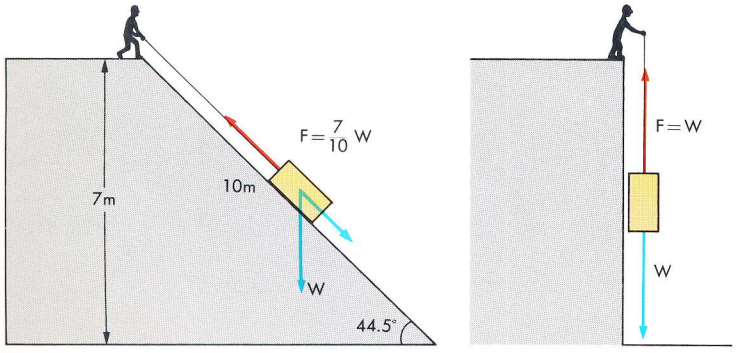
The screw of a jack exploits the great forces generated by rotating screws to lift heavy objects such as cars and lorries. Turning the central screw with the help of a lever causes the two ends of the jack to draw together, producing the necessary lift.



Inclined planes for splitting

A wedge consists of two inclined planes joined back to back. When pounded into a piece of wood, the planes exert lateral forces sufficient to split even the strongest timber.

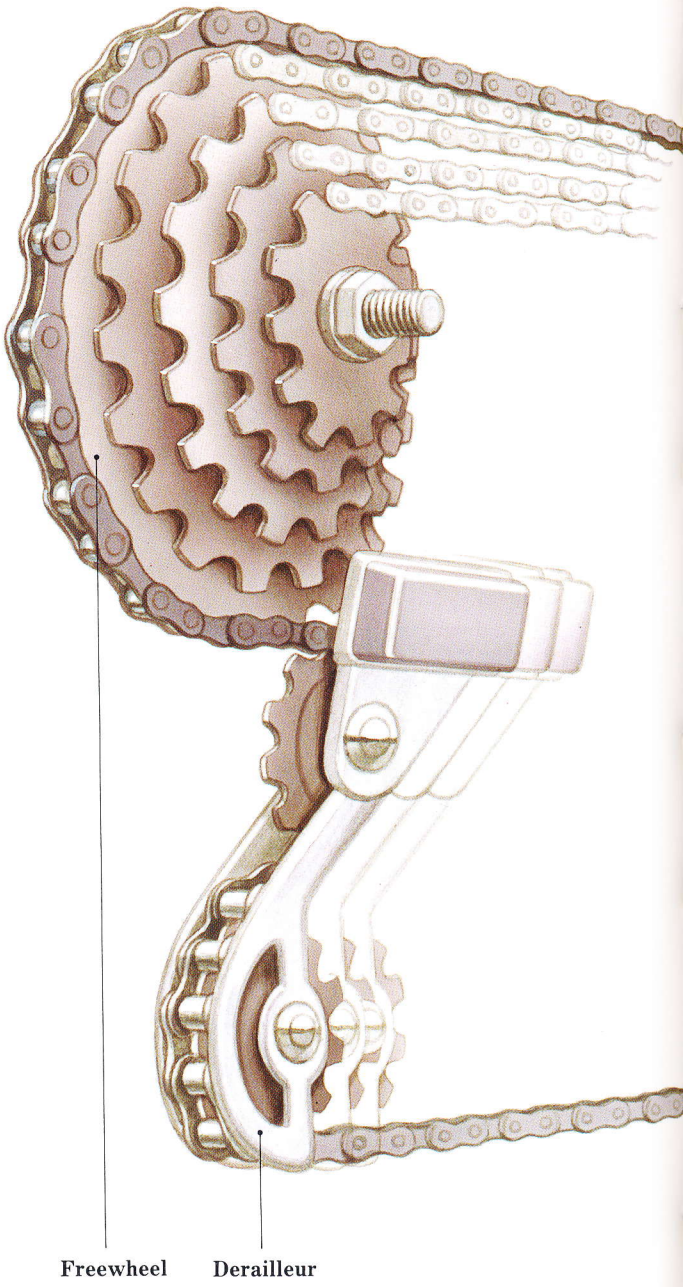




Why do bicycles have gears?

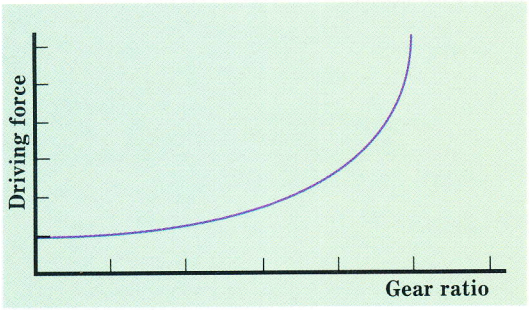
When the ancients turned the lever in a circle around a fulcrum, they discovered another of the simple machines: the wheel and axle. The bicycle uses this principle in the pedal and sprocket. The effort exerted on the rotating pedals turns the sprocket, or chainwheel gear, which connects to a chain that turns another wheel and axle, the freewheel gear attached to the rear wheel. The rider's pedalling force propels the bicycle forward at a faster speed than a person on foot could achieve with the same amount of effort.

Riders can pedal more easily, or increase the mechanical advantage of the wheel and axle, by using a series of gears of different sizes, which magnify or diminish the forces that act on them. Cyclists adjust the gear ratio—the ratio of the size of the chainwheel gear to that of the freewheel gear—to suit the terrain. When the freewheel gear is much smaller than the chainwheel gear, the bike is harder to pedal but it goes faster. A larger freewheel gear allows for easier pedalling but the bike moves more slowly.

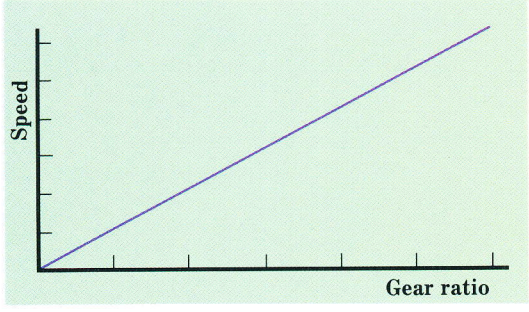


Gear ratios

By using different gear ratios, a cyclist can adjust to varying riding conditions. A low gear ratio provides little force but easier pedalling for uphill climbs, while a high ratio offers greater force for level or downhill stretches when pedalling is easy.



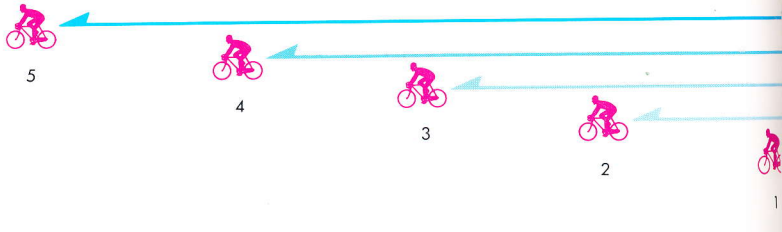
Gear ratio and driving force



Gear ratio and speed

The freewheel gears

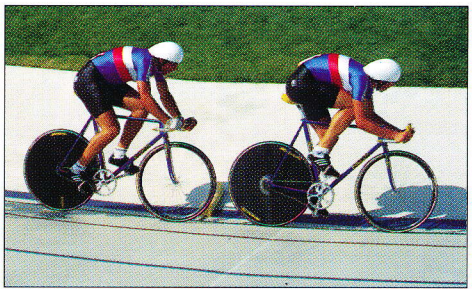
The smaller the freewheel gear, the more revolutions per minute the rear wheel will make with one turn of the pedals. The chart below shows the distances a bicycle travels after one pedal revolution for five different freewheel gears.



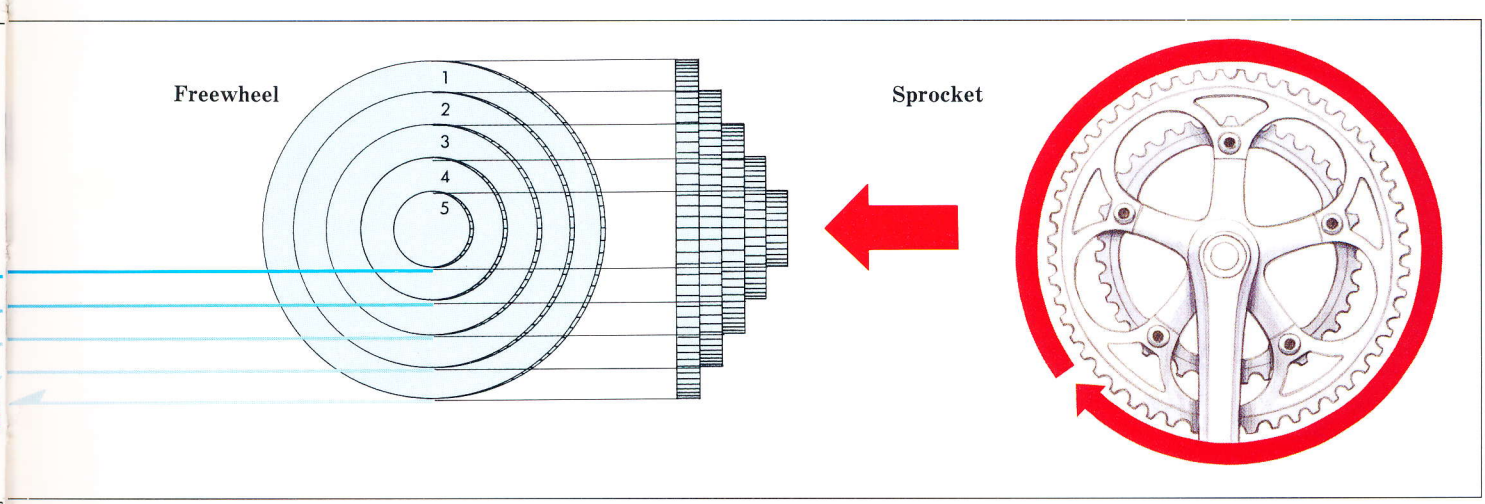
Combining gears

The chainwheel and freewheel gears vary greatly in size and number of teeth. To shift gears smoothly while in motion, multispeed bicycles use devices called derailleurs that move the chain from one gear to the next.

Sprocket



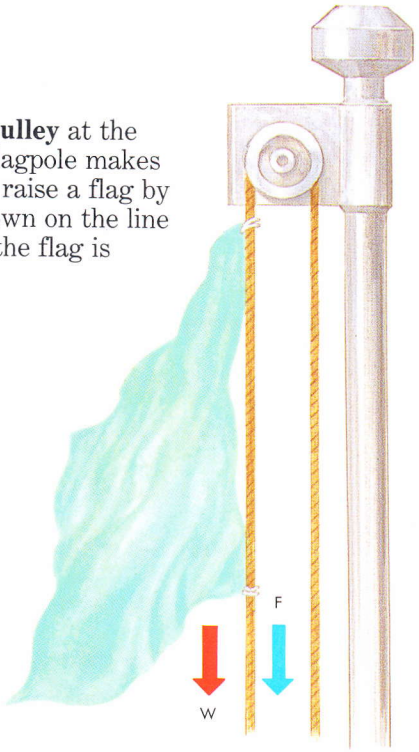
Pedal power speeds bicycles along



How do pulleys work?

A pulley consists of a chain or a belt passed around a wheel or a series of wheels. Like the lever, a pulley can reduce the effort needed to raise an object, but a pulley can also redirect the applied force. Such an advantage comes at a cost: The smaller the effort needed to lift a weight, the longer the distance through which the effort must move. A combination of pulleys multiplies the advantage by the number of weight-bearing chains used, according to the simple equation $F = \frac{1}{n} W$ where F is the force needed to move the object, n the number of weight-bearing chains, and W the weight of the object.

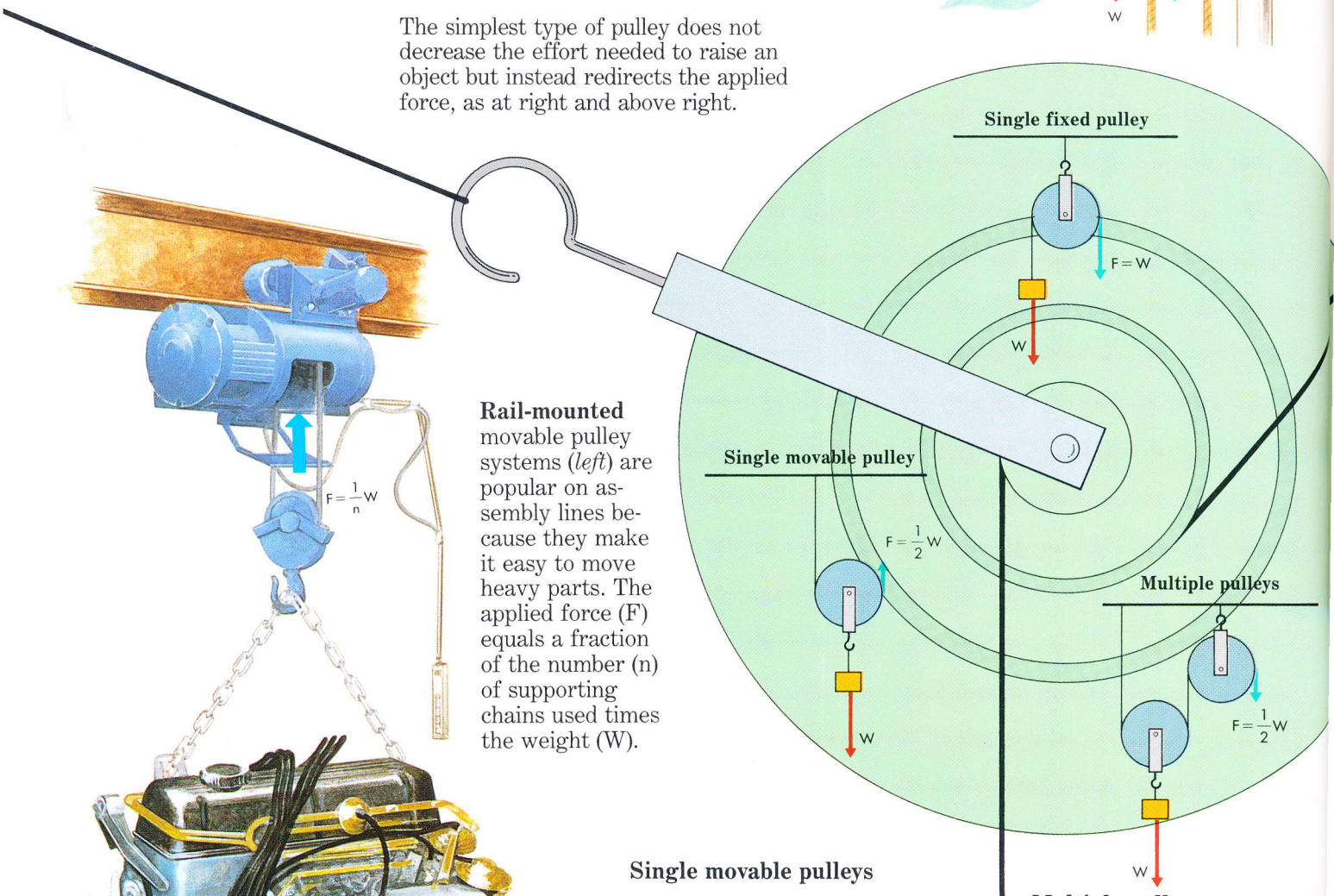
These effort-saving devices serve many purposes, ranging from hoisting massive steel beams at building sites to raising flags. As with the other simple machines, the pulleys' exact origins are unknown. They were first documented in the fifth century BC, when the ancient Greeks used them in ships and theatres.



A fixed pulley at the top of a flagpole makes it easy to raise a flag by pulling down on the line to which the flag is attached.

Single fixed pulleys

The simplest type of pulley does not decrease the effort needed to raise an object but instead redirects the applied force, as at right and above right.



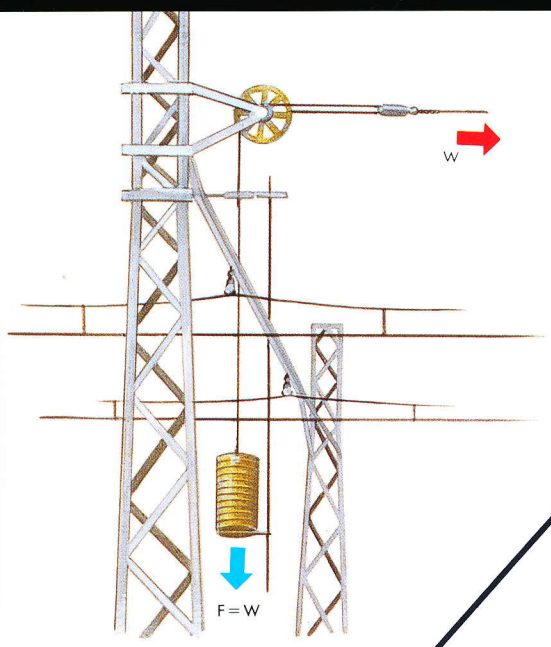
Rail-mounted movable pulley systems (*left*) are popular on assembly lines because they make it easy to move heavy parts. The applied force (F) equals a fraction of the number (n) of supporting chains used times the weight (W).

Single movable pulleys

When allowed to move, a single pulley (*above*) cuts in half the effort required to raise an object. But applying half the force means the object will have to be moved twice as far, or force equals half the weight ($F = \frac{1}{2}W$).

Multiple pulleys

By using a combination of fixed and moving pulleys (*above*), the applied force is multiplied by the total number of weight-bearing chains used. Here, with two such chains, force equals half the weight ($F = \frac{1}{2}W$).



A weight hanging vertically from a pulley keeps horizontal electrical wires taut.

A free hoist (*right*) features a chain looped around one movable and two fixed pulleys. Two sections of the chain bear weight, so raising the load requires an applied force of just half the load's weight.

A block and tackle, often used with large cranes (*right*), consists of a set of pulleys attached to the load and a fixed set attached to the crane's boom. With the mechanical advantage gained from so many pulleys, the crane can lift extremely heavy objects like steel beams. Expressed as an equation, force (F) equals a fraction of the number (n) of supporting cables times the weight (W).

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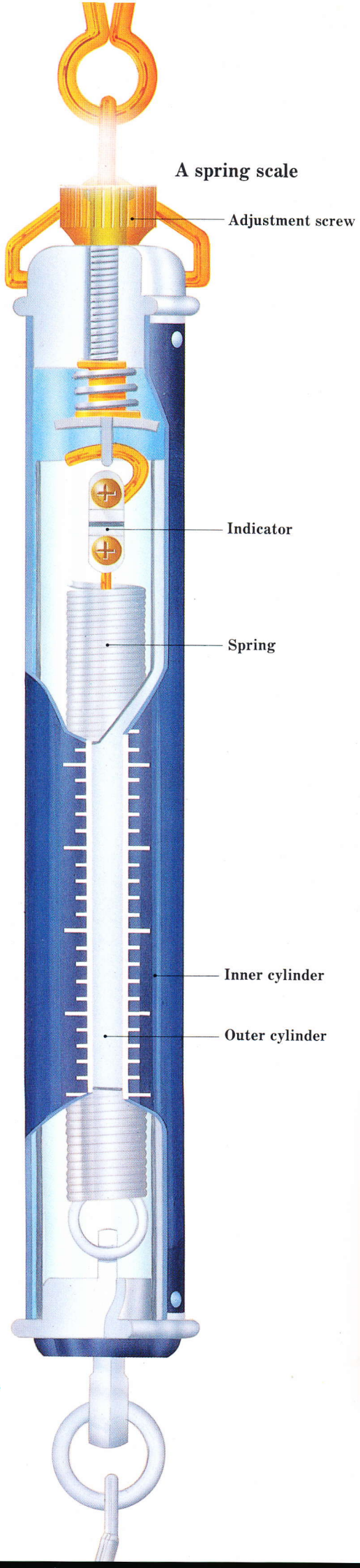
How can springs measure forces?

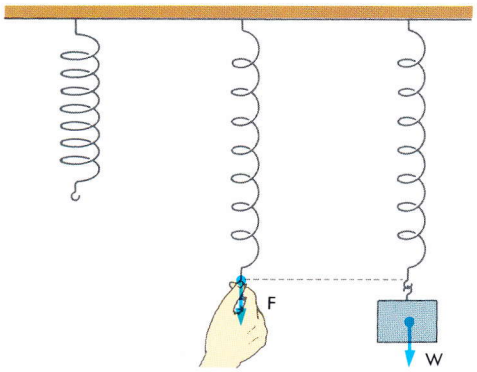
Springs are mechanical devices that stretch and compress according to a simple law. First formulated in 1678 by English physicist Robert Hooke, this law, appropriately called Hooke's law, states that springs deform proportionally to the forces acting on them. Simply put, the greater the force pulling or pushing on a spring, the farther the spring will stretch or compress. Beyond a certain point known as the elastic limit, the bonds that link the spring's atoms will shift and permanently distort the spring, which will never recoil again.

The elasticity of springs makes them useful in scales and balances. A comparison between how much a spring is stretched by an unknown weight and a known weight makes it easy to calculate the unknown weight.



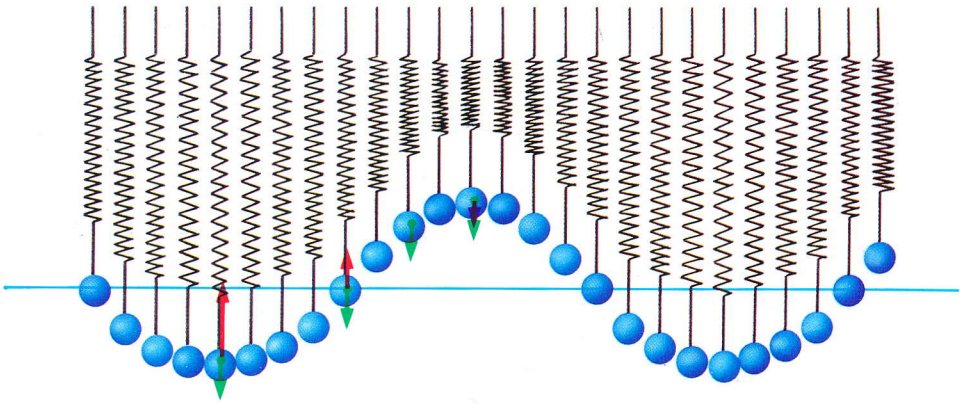
Springs and forces

A spring will always stretch the same distance when subjected to the same force. If the person applying a force (F) and the block applying a weight (W) stretch the spring equally far, the force must equal the weight.



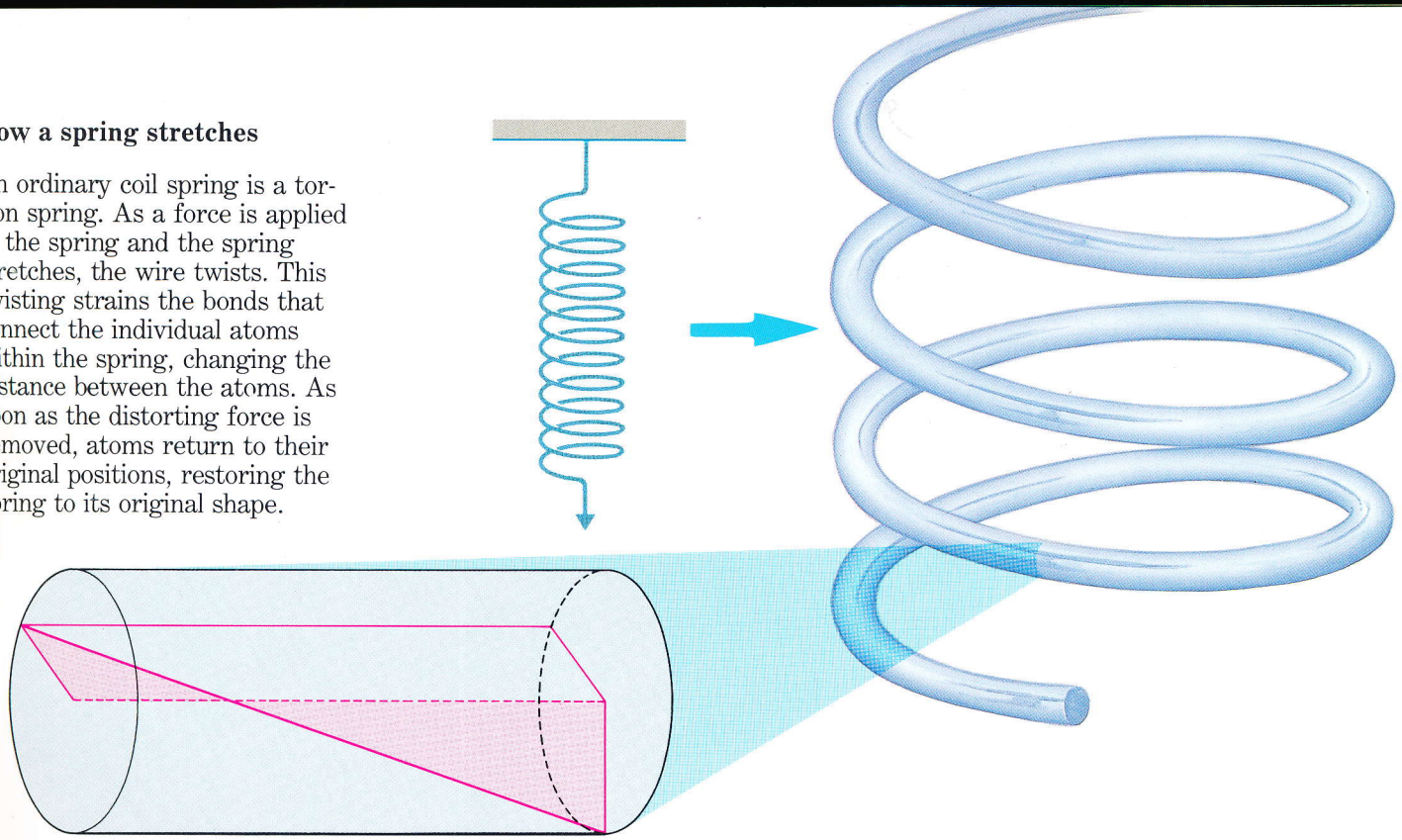
The bounce in a spring

Pulling and releasing a weight attached to a spring will generate the curve shown below; red arrows indicate the spring force and green arrows the weight. If it were not for friction, which slows these motions, the springs would stretch and compress forever.



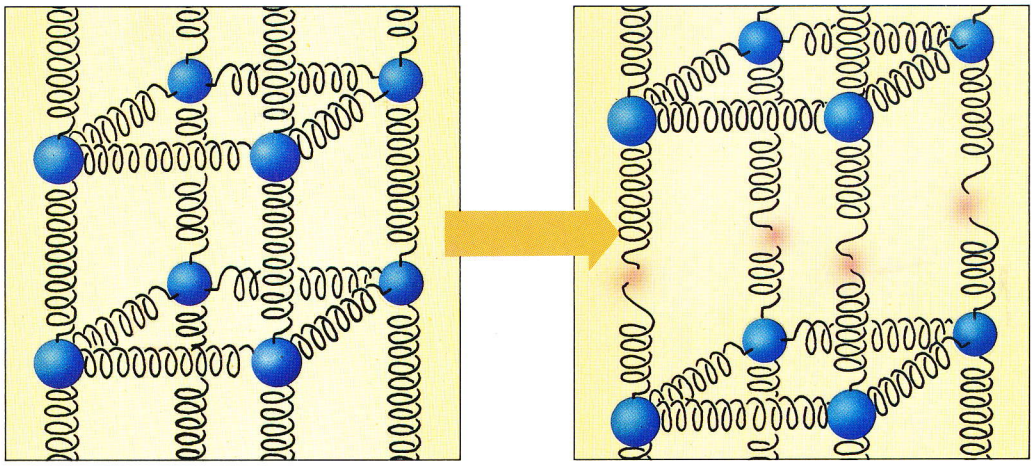
How a spring stretches

An ordinary coil spring is a torsion spring. As a force is applied to the spring and the spring stretches, the wire twists. This twisting strains the bonds that connect the individual atoms within the spring, changing the distance between the atoms. As soon as the distorting force is removed, atoms return to their original positions, restoring the spring to its original shape.

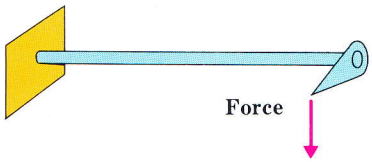


Elasticity

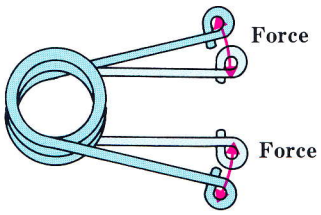
The atoms in a metal spring act as if they were connected by springs. When compressed, the atoms' tendency is to push back to their normal position. When driven apart, they tend to pull back toward each other, restoring the metal's original shape. If the atoms stretch beyond their elastic limit, the bonds connecting them break, and the metal is bent permanently into a new shape.



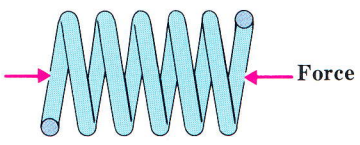
Torsion and bar springs



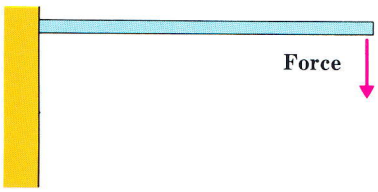
Torsion springs consist of twistable rods that revert to their original shape when released.



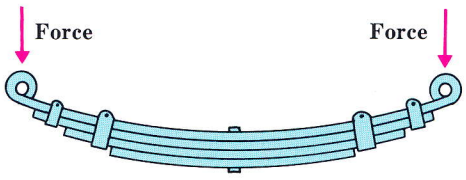
Helical springs work in shears by pushing the blades apart when pressure on the grips is released.



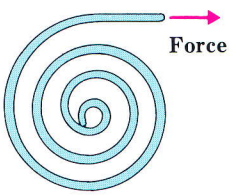
The most common helical spring can be found in objects such as ballpoint pens and shock absorbers.



A flat spring simply consists of a bar that flattens out again after having been bent.



Made of several arched metal bars, leaf springs are similar to flat springs, but much stronger.



Coil springs, used in traditional wristwatches, can be wound tightly and fit in small spaces.

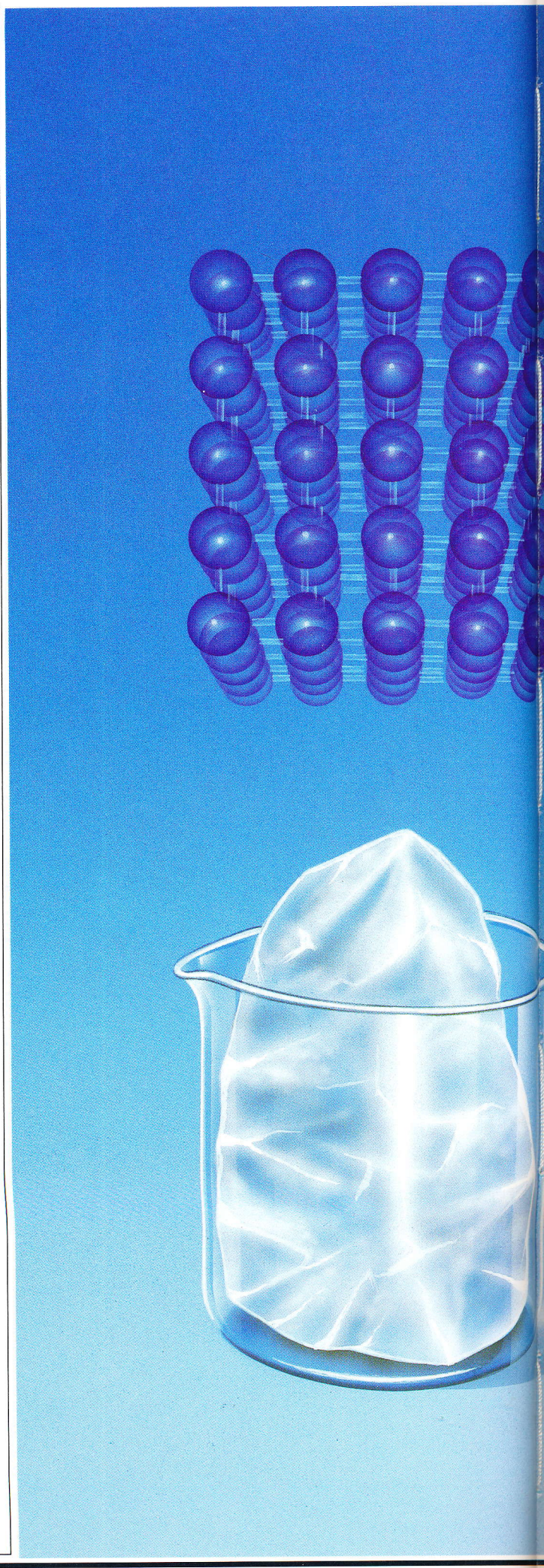
4

Temperature, heat, and molecules

In everyday terms, temperature, as measured by a thermometer, indicates the relative warmth or coolness of things. In scientific terms, temperature is a measure of the average kinetic energy of a substance's molecules. This kinetic energy reflects how fast the molecules move. In water at 50° Celsius, the water molecules have more kinetic energy and are moving faster than the molecules in water at 5° Celsius.

Although thermal energy and heat energy are often spoken of interchangeably, they are not the same thing. Thermal energy, as measured with a thermometer, is the amount of energy a substance has because its molecules are moving. Heat energy is a measure of the sum total of the energies of all its molecules. For example, a 2-kilogram block of ice contains twice as much heat energy as a 1-kilogram block of ice, even though their temperatures are the same.

This chapter will show how heat can move from a warmer substance to a cooler one or through fluids such as water and air. But heat does more than travel. At 0° Celsius, heat changes solid ice to liquid water. At 100° Celsius—the temperature at which water boils—heat changes liquid water to the gas called water vapour. Nearly all other substances also undergo such changes at their own distinctive temperatures. Each of these transformations—called a phase change, or a change in the state of matter—is caused by heat.



Molecular organization is the difference between ice, liquid water, and water vapour. In ice (*right*), slow-moving molecules are tightly bonded. Heat loosens these bonds (*middle*), melting the ice; more heat frees the molecules as gas (*far right*).

Why does ice stay cold as it melts?

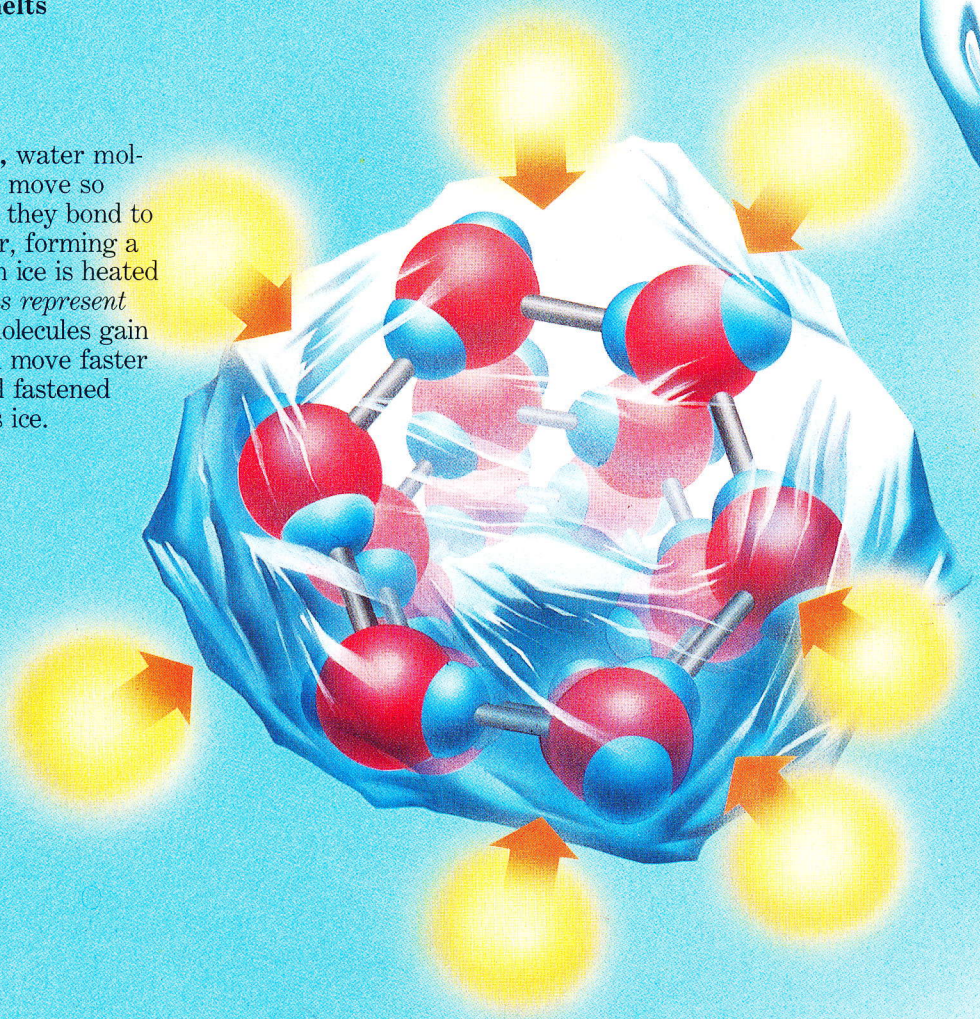
When ice is placed in a pot on a stove and the heat is turned on, the pot gets warm and the ice begins to melt. But as long as there is ice in the water, the water's temperature never rises above 0° Celsius, no matter how hot the burner gets. That's because all of the heat goes into the ice to break the physical forces that bind water molecules together as ice.

The water molecules in ice are held together by weak bonds that form between a hydrogen atom (*blue*) on one water molecule and the oxygen atom (*red*) of another water molecule. The resulting hexagonal crystal structure is fairly strong. At 0° Celsius, the molecules move enough to weaken the bonds. Some of the bonds break, allowing water molecules to escape the ice as liquid. This melting process is called a phase change—water changes from its solid phase to its liquid phase—and the temperature at which it occurs is called the melting point.

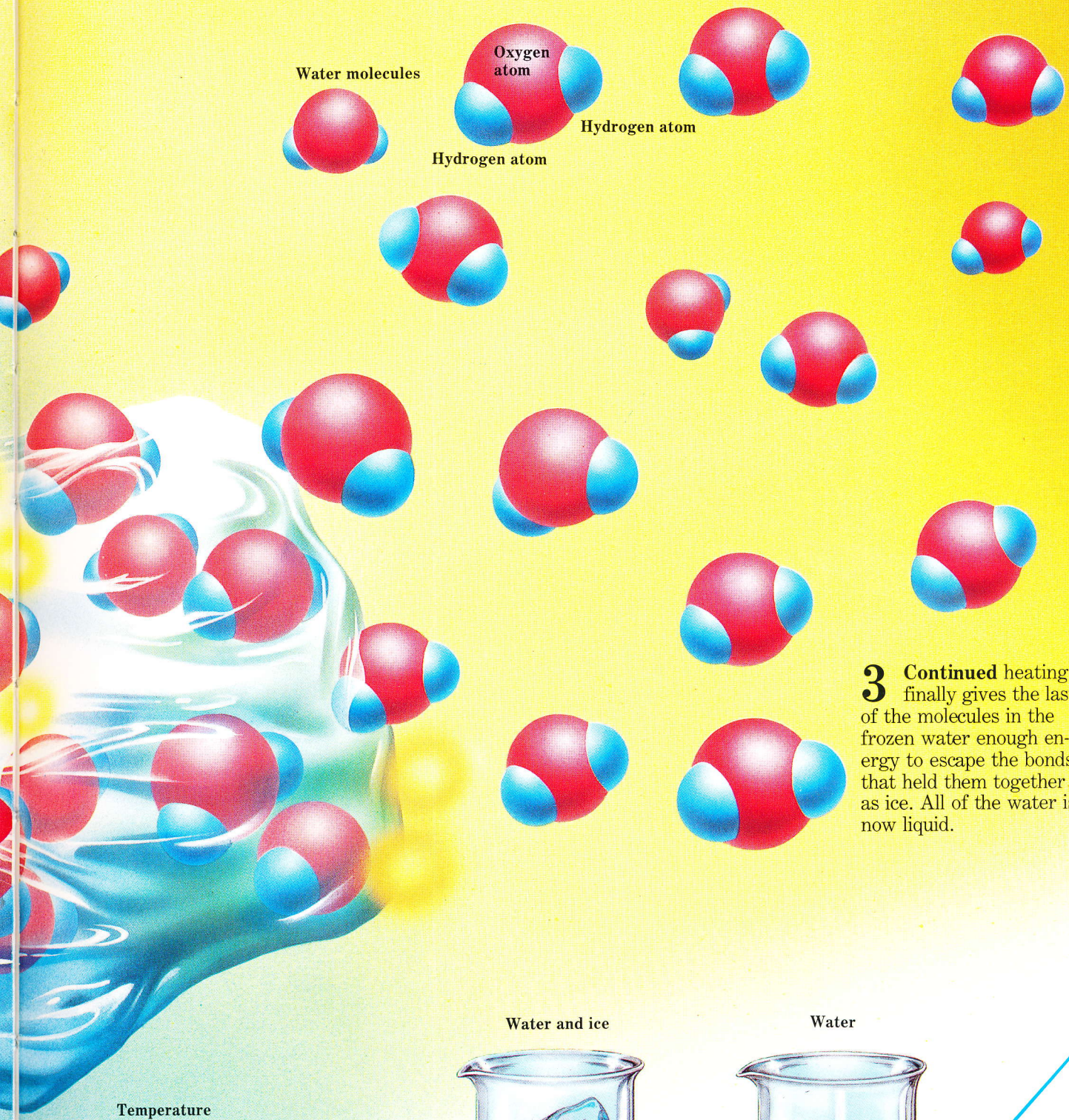
Breaking the bonds that hold water together as ice requires energy—so much energy that all of the burner's heat goes into severing those bonds instead of raising the ice's temperature. The heat needed to complete the phase change is called the latent heat of fusion or heat of transformation, as it does not cause the temperature to rise. Only when the last bonds break and all the ice is melted does the water temperature rise above 0° Celsius.

How ice melts

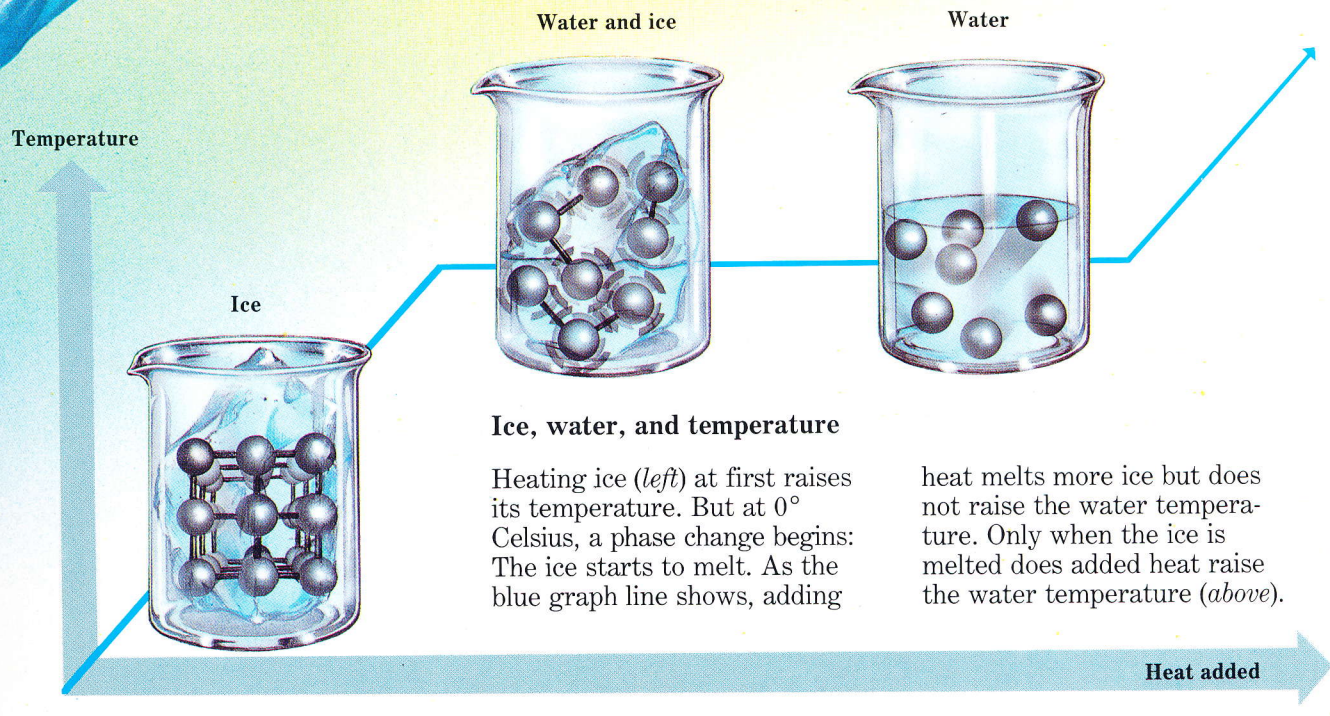
1 **In ice,** water molecules move so slowly that they bond to one another, forming a solid. When ice is heated (*yellow balls represent heat*) the molecules gain energy and move faster but are still fastened together as ice.



2 **When more heat** is added, water molecules at the surface of the ice vibrate faster, breaking some of the bonds holding them in place. These molecules escape from the ice as liquid water. More heat will break the remaining bonds and melt the rest of the ice.



3 **Continued** heating finally gives the last of the molecules in the frozen water enough energy to escape the bonds that held them together as ice. All of the water is now liquid.



Ice, water, and temperature

Heating ice (*left*) at first raises its temperature. But at 0° Celsius, a phase change begins: The ice starts to melt. As the blue graph line shows, adding heat melts more ice but does not raise the water temperature. Only when the ice is melted does added heat raise the water temperature (*above*).

How is extreme heat measured?

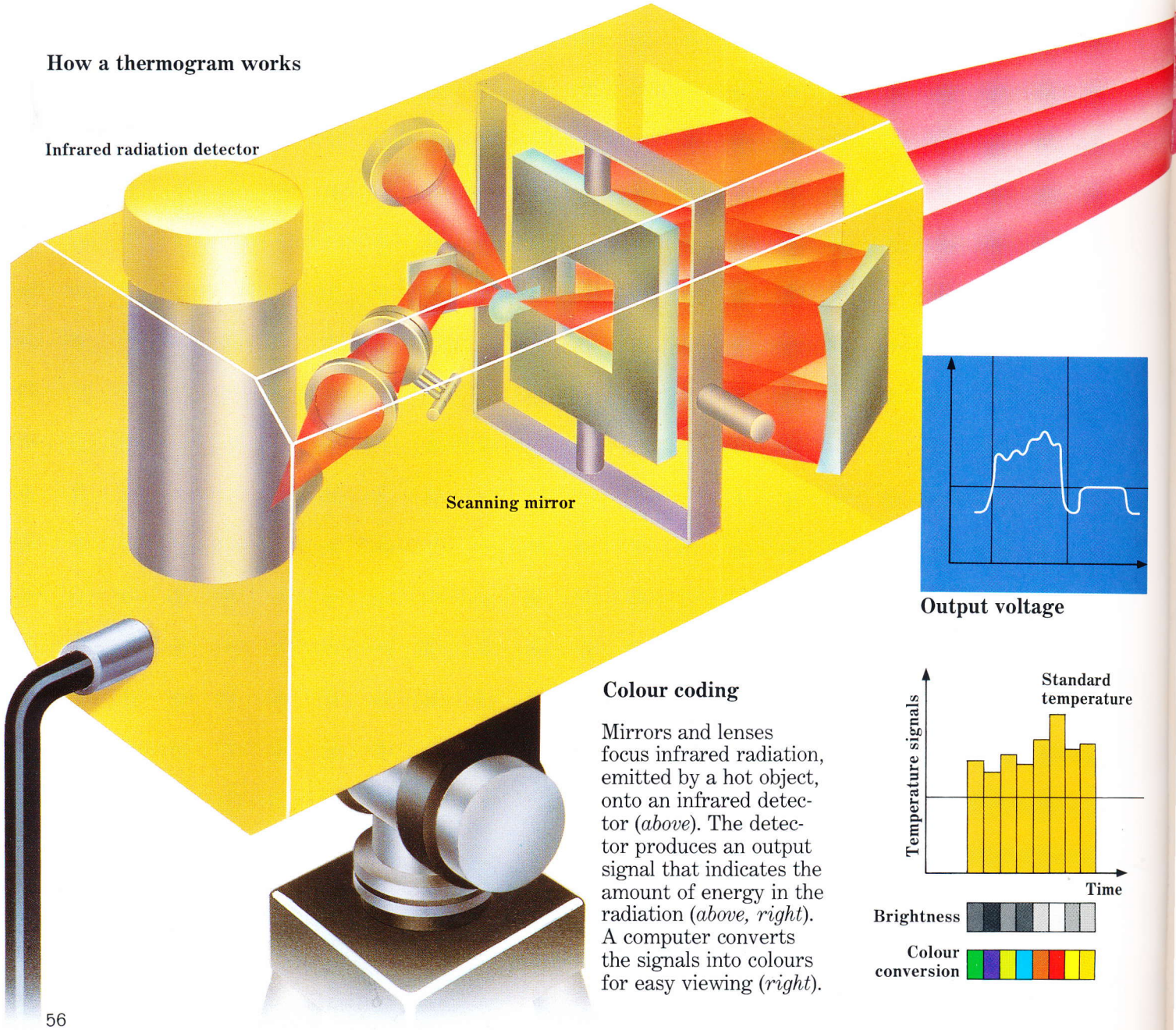
Measuring the air temperature on a very hot day is a simple matter of exposing a thermometer to the air. But trying the same approach with molten iron straight from a blast furnace, at temperatures exceeding 1,500° Celsius, yields nothing more than a melted thermometer. Determining such extreme temperatures depends on measuring the radiant thermal energy that all hot objects emit.

Radiant thermal energy is infrared radiation—like light, a form of electromagnetic radiation. Though infrared radiation is invisible, special electronic devices can detect it. These detectors convert the energy of infrared radiation to an electric signal. The greater the infrared energy striking the detector, the stronger the signal.

In a thermogram, which is one type of high-temperature thermometer (*below*), the infrared detector senses the radiation from the hot object, and scanners select a series of points on the object to assess temperature distribution. A computer compares signals from the two sources and determines the temperature of the hot object. Thermograms measure temperatures up to 900° Celsius.

Objects that are extremely hot emit visible as well as infrared radiation. An optical pyrometer of the disappearing-filament variety is able to measure temperatures up to 3,000° Celsius, by matching a hot object's brightness to that of a tungsten light-bulb filament that is of known temperature.

How a thermogram works



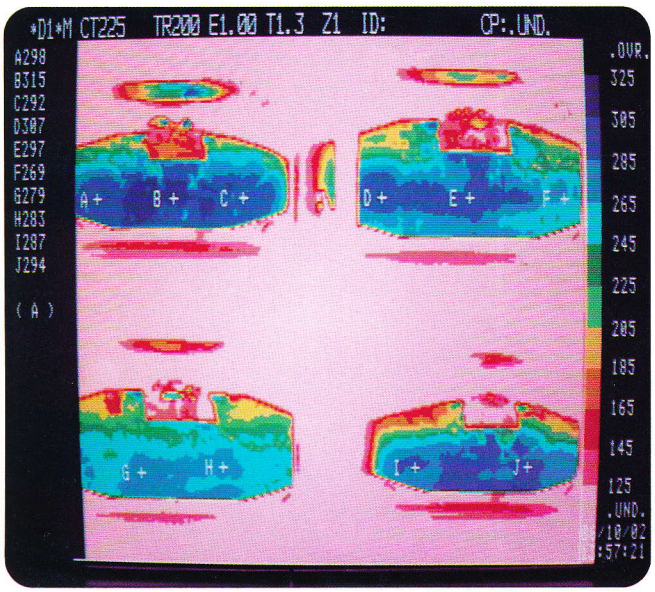
Colour coding

Mirrors and lenses focus infrared radiation, emitted by a hot object, onto an infrared detector (*above*). The detector produces an output signal that indicates the amount of energy in the radiation (*above, right*). A computer converts the signals into colours for easy viewing (*right*).

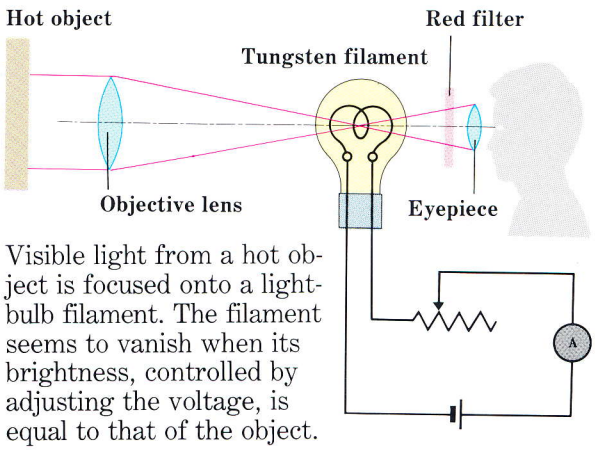
A thermogram scans a torpedo car filled with molten pig iron. The iron, straight from a blast furnace, is on its way to another furnace to be made into steel.

The thermogram's view of molten iron

A computer assembles the output voltage signals from the thermogram (*left*) into a colour-coded map of each torpedo car's temperature (*below*). The colour key on the right shows that dark blue marks the hottest areas. Four torpedo cars are temperature-mapped on this screen.



An optical pyrometer



Visible light from a hot object is focused onto a light-bulb filament. The filament seems to vanish when its brightness, controlled by adjusting the voltage, is equal to that of the object.

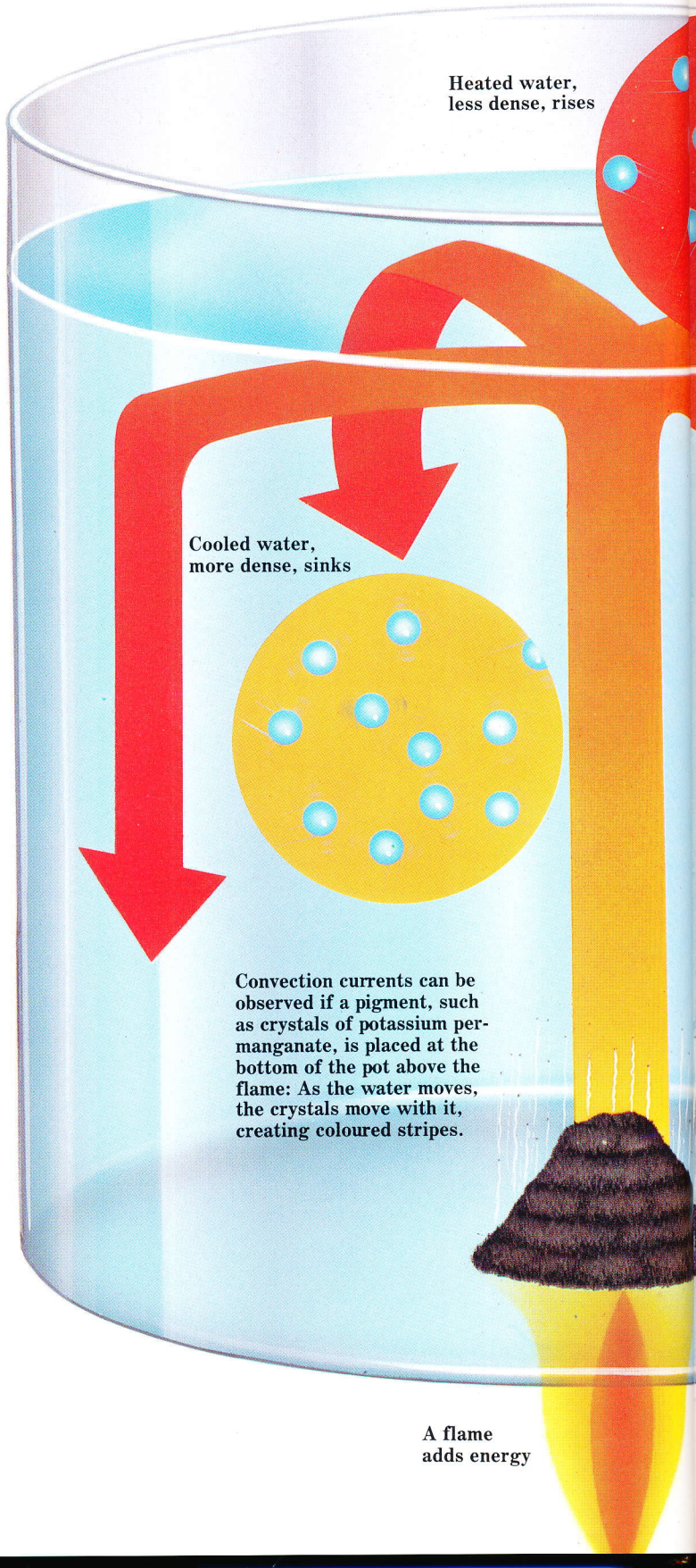
How does heat spread in fluids?

Heating any fluid—such as water or air—forces it to expand, making it lighter. Similarly, cooling a fluid makes it contract and become heavier. The combination of these opposite physical events forms the phenomenon called convection, a process that transfers heat throughout large volumes of any liquid or gas.

When a pot of water sits on a burner (*right*), water over the flame absorbs energy. This energy causes the water molecules to move apart from one another, making the water less dense. The warmed water (*orange column*) rises. At the same time, colder, denser water (*red arrows*) sinks from the top to replace the warm water. As the hot water rises, it loses energy to the water through which it passes and cools somewhat. Meanwhile, warmer water keeps rising, pushing aside the now-cooled water. Convection stops after the flame goes out and all the water reaches the same temperature.

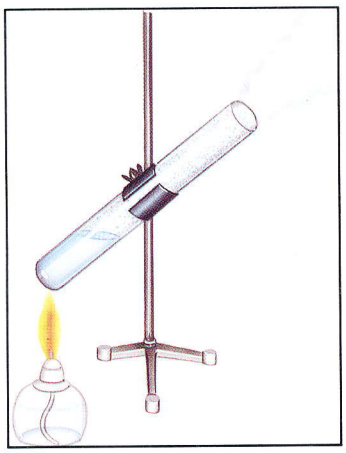
Convective water movement

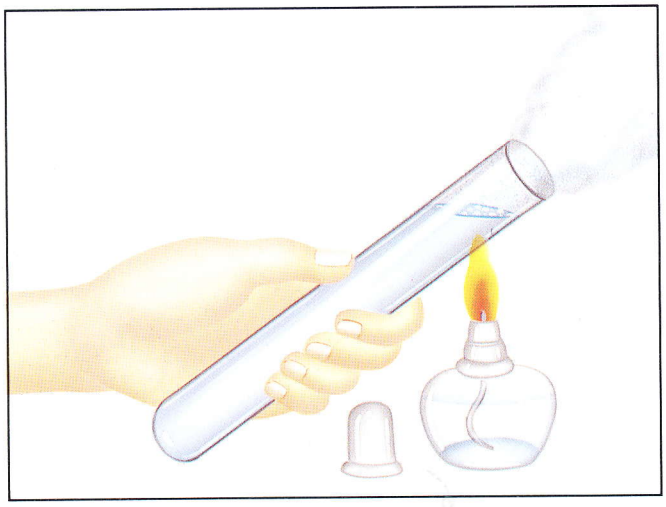
Warmed water loses heat as it rises from the bottom of a heated beaker. At the surface, still-warmer water below pushes it aside. As it cools, the water becomes denser and sinks.



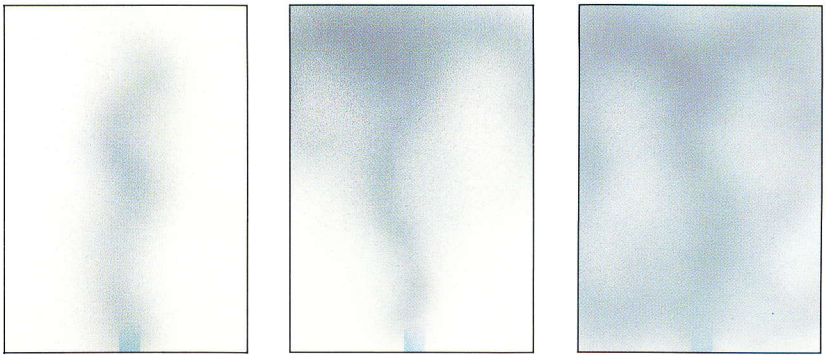
Convection by heating

Heating the bottom of a test tube (*right*) warms the water there. The warm water then rises, as cooler, heavier water sinks and is heated. Eventually, all the water becomes warm. Heating the top of the tube (*below*) warms only the water at the top since warm, light water stays above cold water.

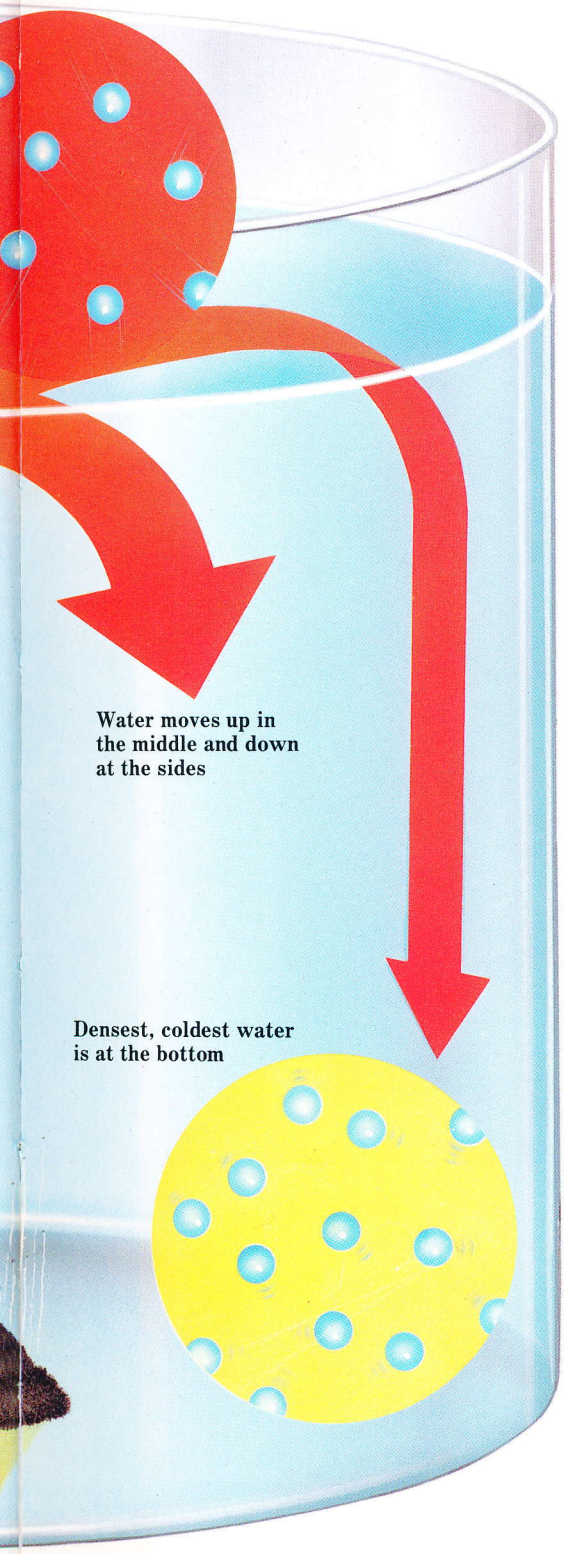




Convection in a gas

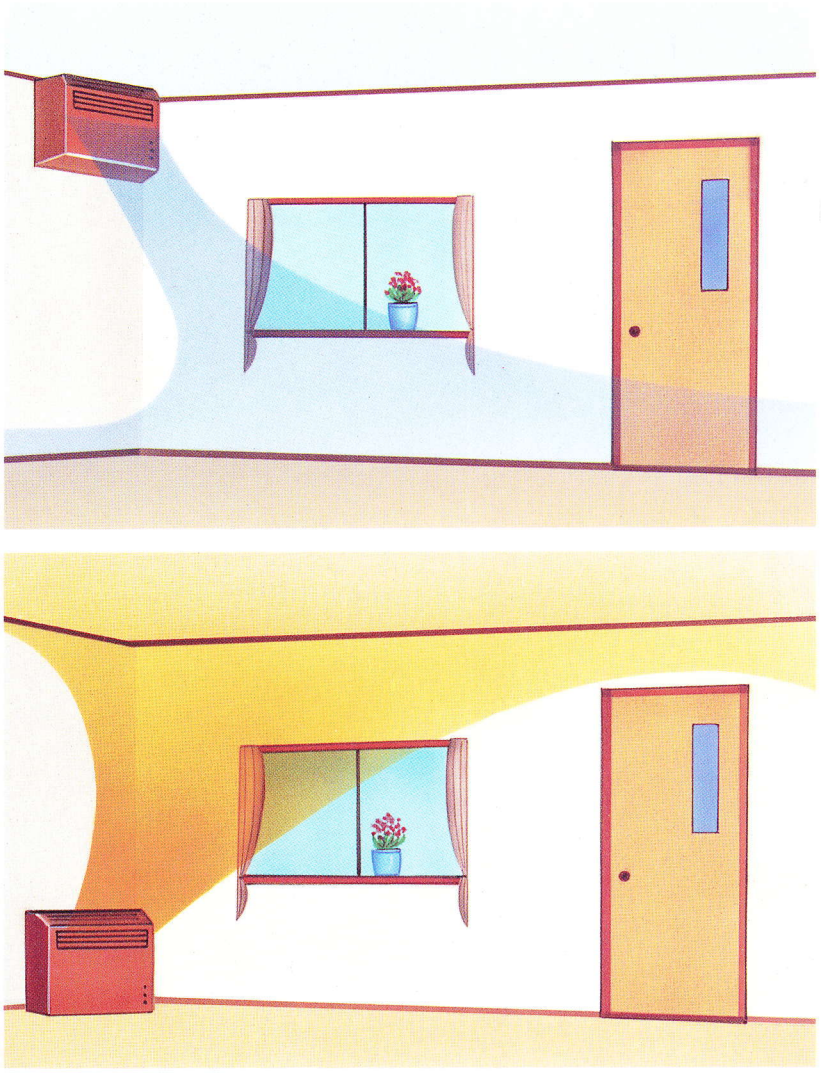


Smoke shows how convection currents form in air (*above*). The process starts (*left*) when warm air rises in a room. When the warm air reaches the ceiling (*middle*), it spreads outward as more warm air pushes it aside. As it loses heat, this air now sinks back to the floor. Pushed back to the heat source by cool, trailing air (*right*), the air is warmed and rises again.



Heating and cooling a room

An air conditioner cools a room most efficiently if it is near the ceiling (*top*) because cooled air (*blue*) sinks, then spreads by convection. Similarly, a heater works best when placed near the floor (*bottom*). Warm air (*orange*) rises and then circulates in the room.



What makes a down jacket so warm?

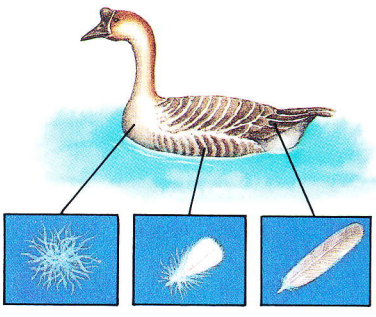
Anyone who goes outside in cold weather without a jacket will feel chilled because the body loses heat by conduction and convection into the cooler air. But inside a down jacket, a warm body stays particularly warm. That is because down—the type of insulating feather that enables geese and ducks to stay warm while floating in cold water—has a structure that makes it difficult for the air that is next to the body to move away into colder air. When air is unable to move, it cannot carry heat away.

Heat always flows from an area that is warm to one that is cooler. A warm body loses heat when air molecules pick up energy, speed up, and move farther apart, away from warm skin. Each air molecule carries a small amount of energy. The more energy molecules take away, the colder a person feels.

Down dramatically slows heat loss by interfering with the process of convection. Each down feather has thousands of tiny hairlike projections known as barbules. The barbules of neighbouring feathers interlock with one another, forming a fine net that impedes the movement of air. With air motion reduced, heat convection drops as well, and the body stays warm.

How a down jacket insulates

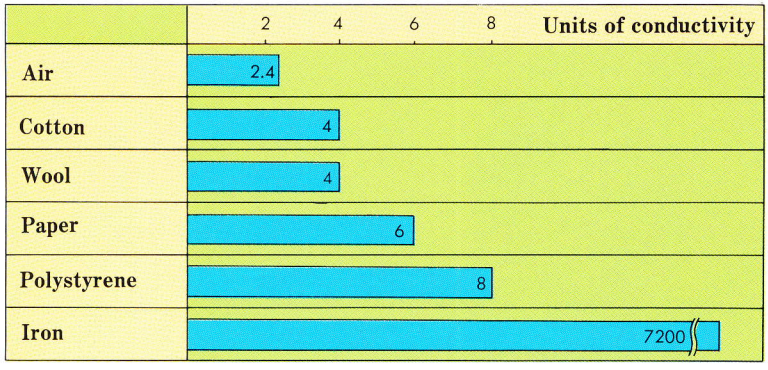
The small feathers, or down, that fill this coat are made of thousands of tiny barbules, or hooks, growing from flexible barbs (*right*). This structure keeps the down from clumping together and losing its insulating capacity.



Feathers. A goose has down feathers (*left*) to keep it warm, semiplumes (*middle*) to help it float, and contour feathers (*right*) to cover the others.

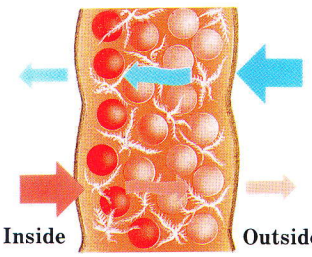
Network. The down's barbules form a net that traps air (*yellow*) in pockets. When air cannot circulate, it does not move heat.

Thermal conductivity



Thermal conductivity measures how heat flows through a substance. Down has a low conductivity of 2.1 and insulates well; so does air, as shown at left. By contrast, iron conducts heat well and is a poor insulator.

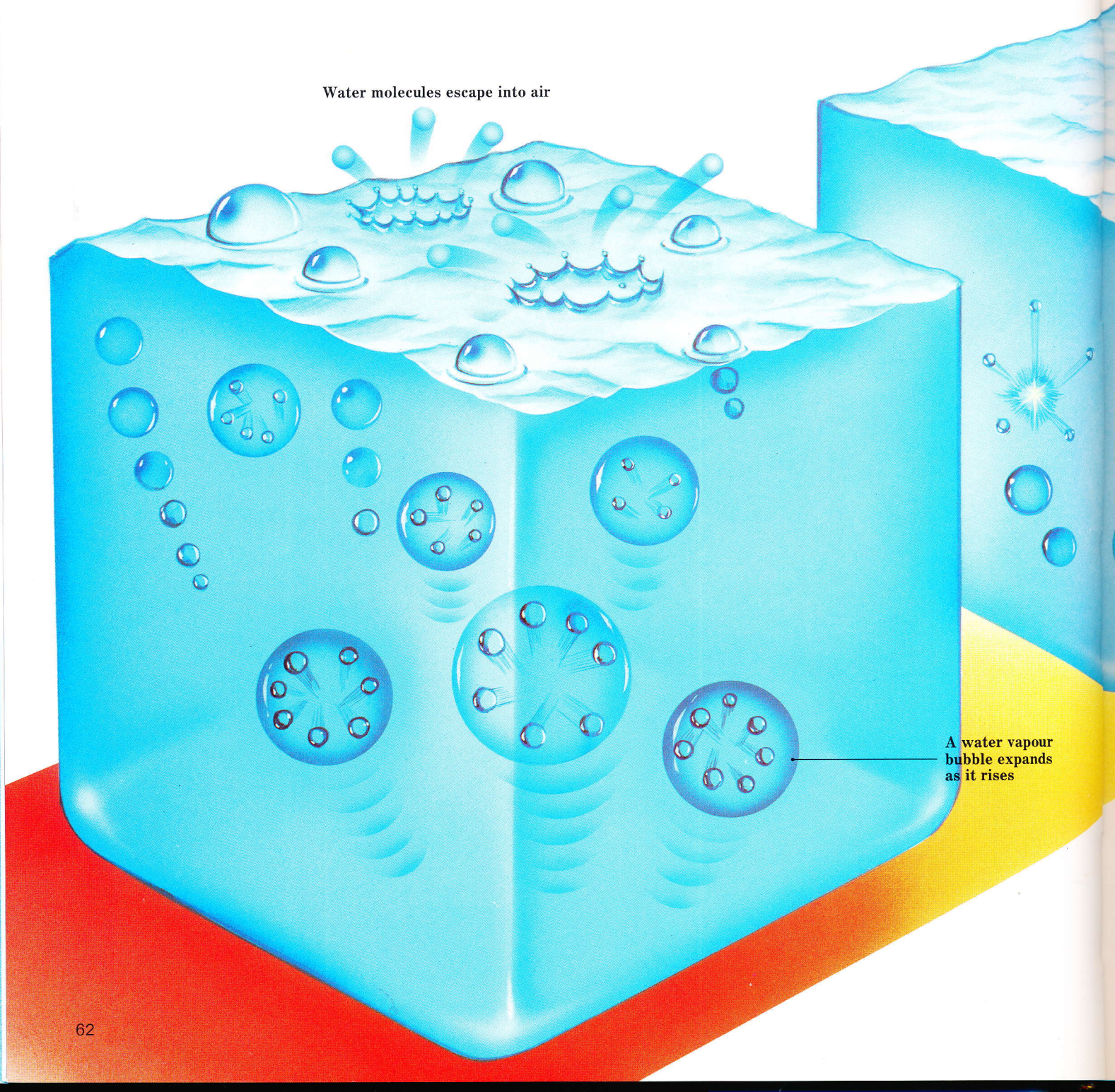
Down impedes the movement of air (*arrows*), thus holding in heat and keeping out cold.



Why does boiling water bubble?

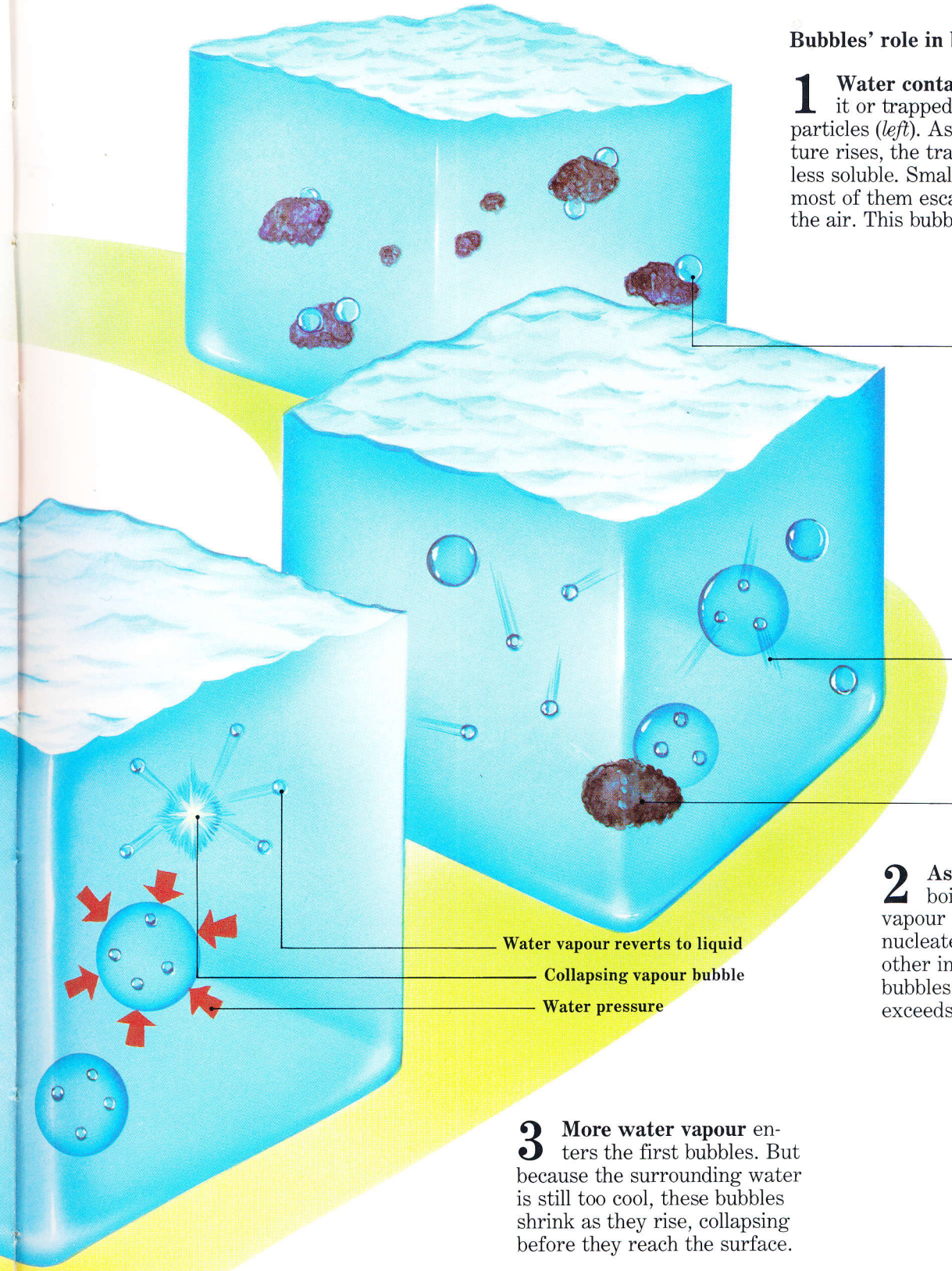
Any liquid, when heated, eventually reaches a temperature at which it starts boiling. Bubbles form throughout the liquid, rise to its surface, and burst, releasing hot vapour into the air. Water boils at 100° Celsius in standard conditions. At the boiling point, every molecule has enough energy to overcome the forces holding it together with other molecules as a liquid. A pot of boiling water, for example, is full of liquid water that is turning into water vapour. At the surface, the water vapour merely escapes the boiling liquid. Beneath the surface, however, the vapour forms bubbles, each containing billions of water molecules, that rise to the top of the water.

Water that is boiling is undergoing a phase change, from the liquid to the gaseous state, in a process called vaporization. Liquids also vaporize at temperatures below the boiling point in a process called evaporation. But evaporation takes place only at the surface at the point when molecules have enough energy to escape the liquid state. While evaporation occurs more quickly when temperatures are higher, only boiling produces bubbles.



Bubbles' role in boiling

1 Water contains air dissolved in it or trapped, clinging to dust particles (*left*). As the water temperature rises, the trapped air becomes less soluble. Small air bubbles form, most of them escaping quickly into the air. This bubbling is not boiling.



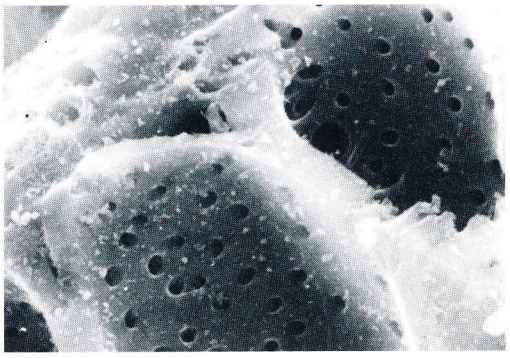
2 As water nears the boiling point, water vapour bubbles form, or nucleate, around dust or other impurities. In these bubbles, the temperature exceeds the boiling point.

3 More water vapour enters the first bubbles. But because the surrounding water is still too cool, these bubbles shrink as they rise, collapsing before they reach the surface.

4 Bubbles form anywhere in the boiling water. These bubbles grow larger as they rise to the surface. There they burst, and water vapour escapes into the atmosphere.

A stone to prevent eruption

In laboratory use, distilled water and other pure liquids, being dust free, offer no place for bubbles to nucleate. In such liquids, a big, sheetlike vapour bubble can form, spilling boiling liquid out of the pot in a dangerous eruption. A stone pocked with tiny holes (*right*) prevents eruption by providing places for bubbles to form gradually.



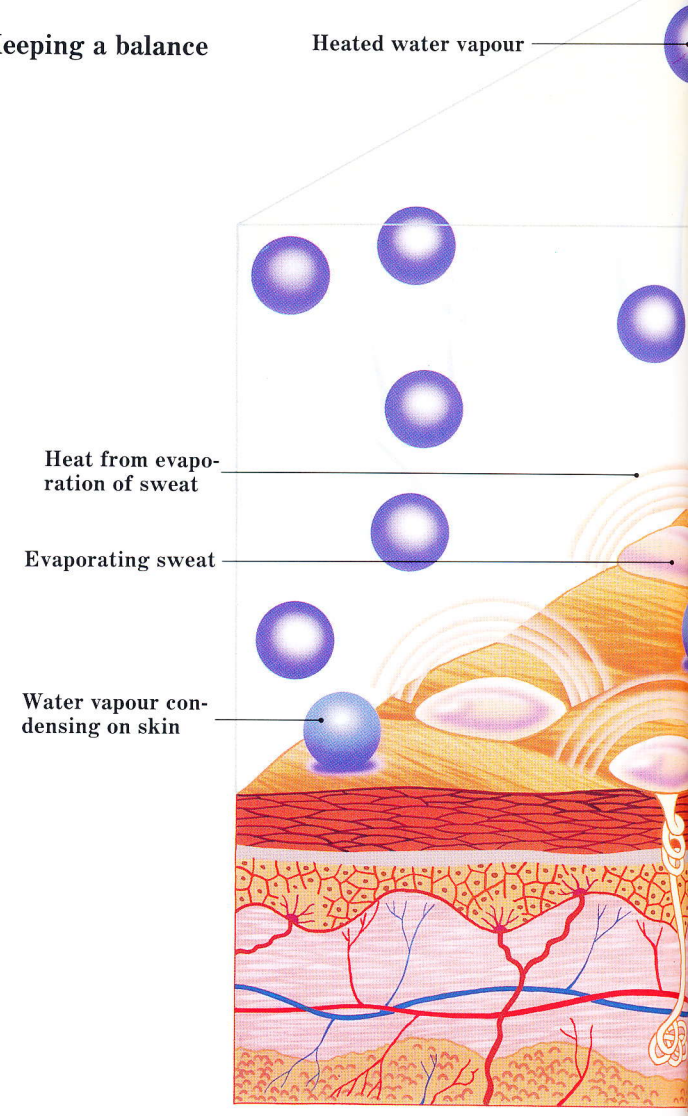
Why doesn't skin burn in a sauna?

In a sauna, the hot, dry air warms the skin immediately but does not burn it. The temperature in a sauna is close to 100° Celsius, the boiling point of water at sea level, which seems hot enough to burn the skin. Indeed, spilling boiling water on the skin would cause a burn. Yet the sauna is a pleasant, not hazardous, experience.

The reason a sauna is safe is that the air inside it has very little moisture. The skin becomes warm in the sauna because energetic air molecules collide with the skin, transferring energy and raising the skin's temperature. But as the skin warms up, it begins to sweat, which is the body's mechanism for maintaining a safe temperature. In the sauna's dry air, sweat evaporates rapidly, taking heat energy with it. If the sauna's air were humid, the skin could not sweat efficiently and would stand a good chance of burning.

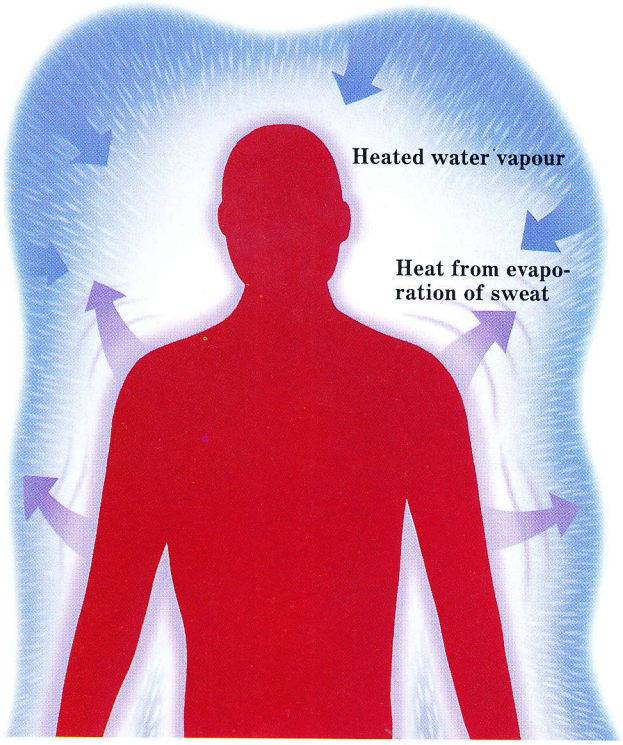
The same principle holds when boiling water strikes skin. In nearly constant contact with the hot water's energetic molecules, the skin has no chance to cool off by sweating. The temperature soars quickly and the skin burns.

Keeping a balance



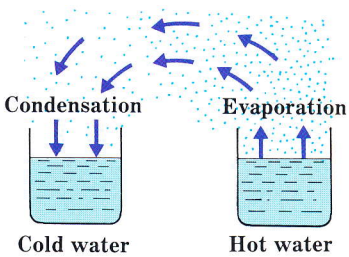
Water vapour and sweat vapour

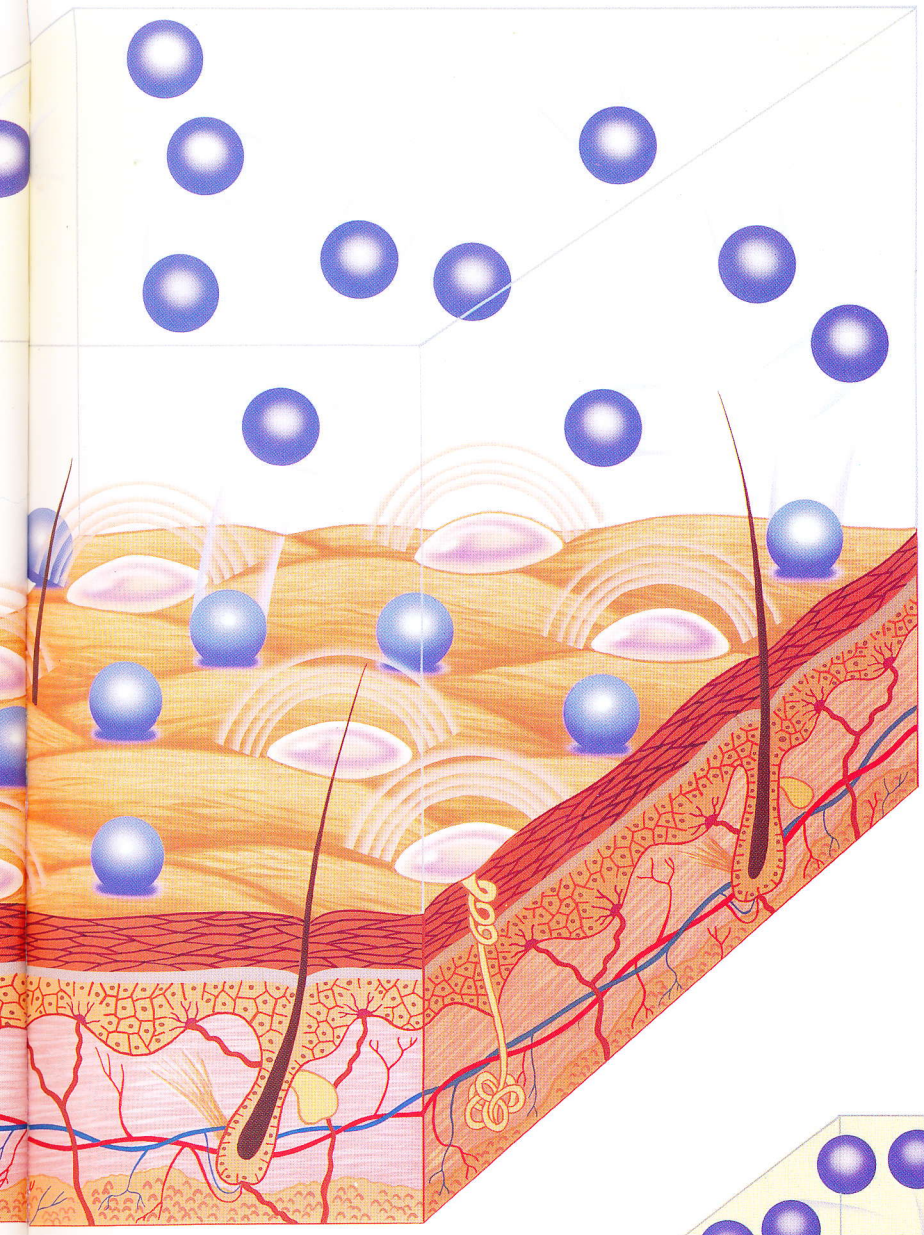
When the skin is cooler than the sauna's air, water vapour in the sauna (*blue arrows*) condenses on the skin, and the skin gains heat. If the skin gains too much heat, it sweats, and sweat evaporating (*purple arrows*) from the skin cools it. Balancing these two processes protects the skin.



How water vapour transfers heat

A beaker of hot water sits near a beaker of cold water. The hot water evaporates, losing heat in this phase change and releasing many water vapour molecules. Some of these move to where water vapour molecules are less numerous, above the cold water. When they meet the cold water, they condense. This phase change adds energy to the cold water, raising its temperature. Movement continues until the beakers have the same temperature.



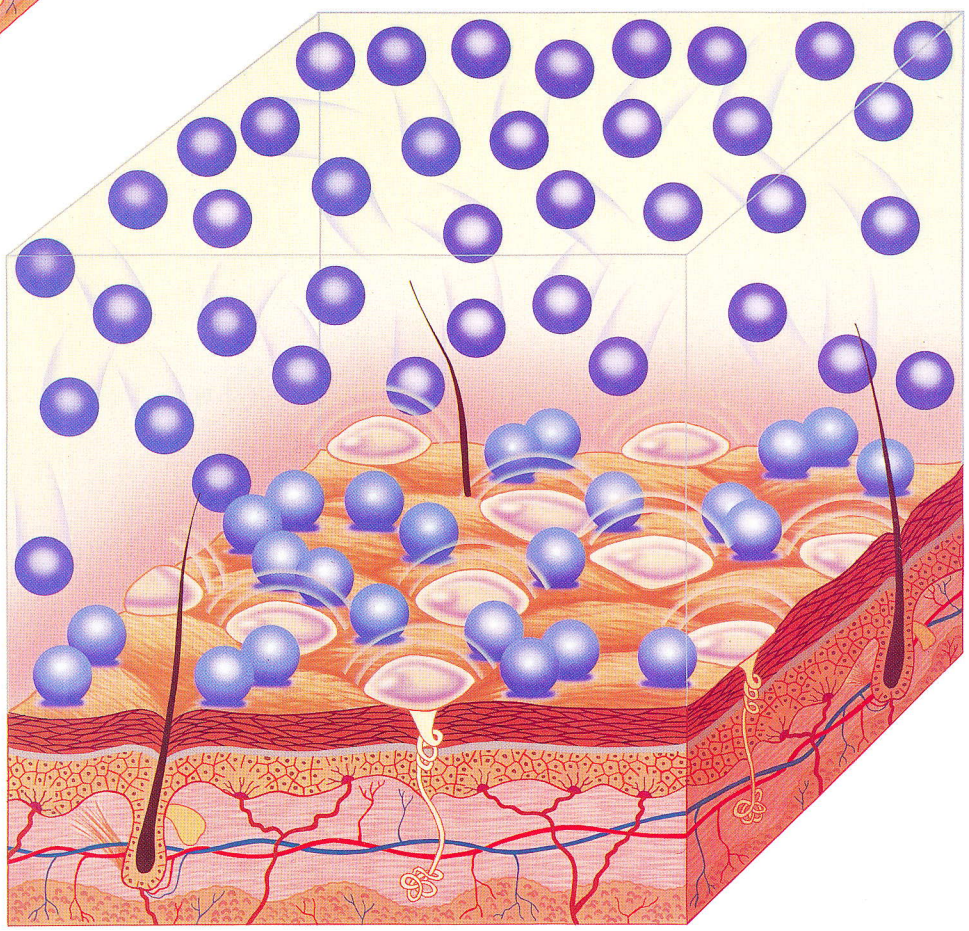


How low humidity protects skin

When the humidity in a sauna is low, as in the diagram at left, the skin can maintain a safe temperature and keep from burning. At low humidity, only a few energetic water vapour molecules (*blue globes*) are present to collide with the skin and condense on it, transferring heat energy to the skin. Thus, the skin absorbs relatively little heat from the dry sauna air. In addition, the low humidity enables the skin to lose excess heat by sweating. As the sweat evaporates from the skin's surface, the departing water vapour molecules take heat energy with them, cooling the skin in the process.

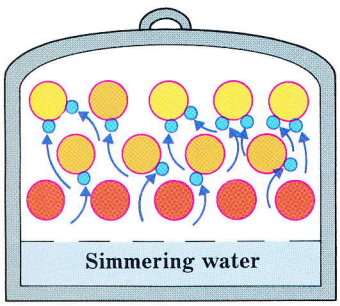
How high humidity burns skin

If the air in a sauna is too humid (*below*), the skin has more trouble regulating its temperature and can suffer burns. At extremely high humidity, many energetic water vapour molecules strike the skin and transfer energy to it. Thus, the skin gains heat more quickly in a moist sauna than in a dry one. And in this more humid air, sweat cannot evaporate as quickly and the skin stays hot longer.



Heating food in a steamer

Food warms evenly in a steamer (*below*) because the hot water vapour can reach it from all sides and condenses only on objects that are cooler than the steam. The cooler the item is, the more steam condenses on it, and the faster it heats.

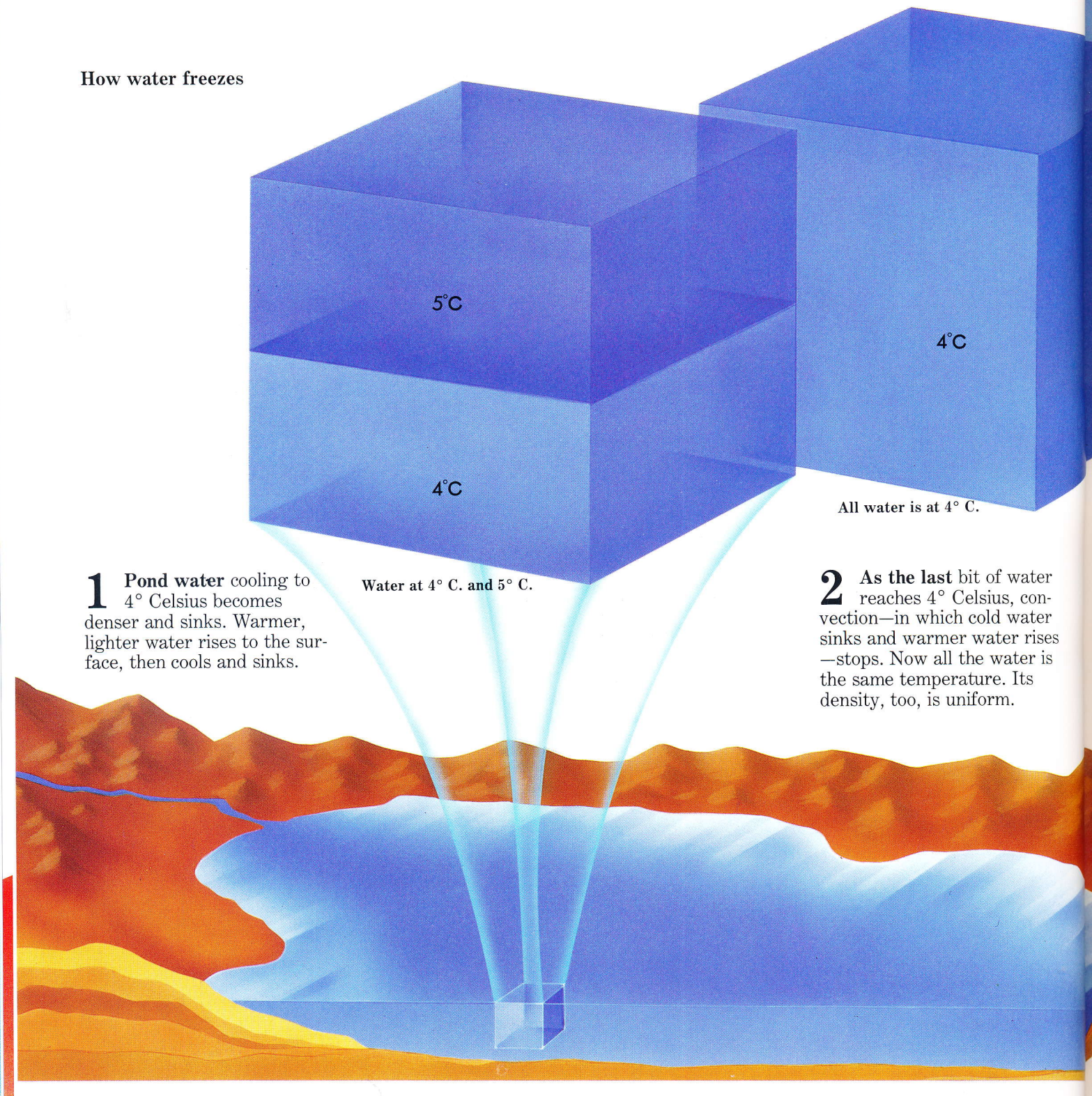


Why does water freeze from the top?

An early sign of winter is ice floating on ponds and lakes. That may not seem unusual or important, but if water acted like almost every other liquid, no one could ever skate on a pond because the ice would sink to the bottom as it formed. What is worse, Earth would probably be a desert, with most of its water lying frozen at the bottoms of oceans, lakes, and streams.

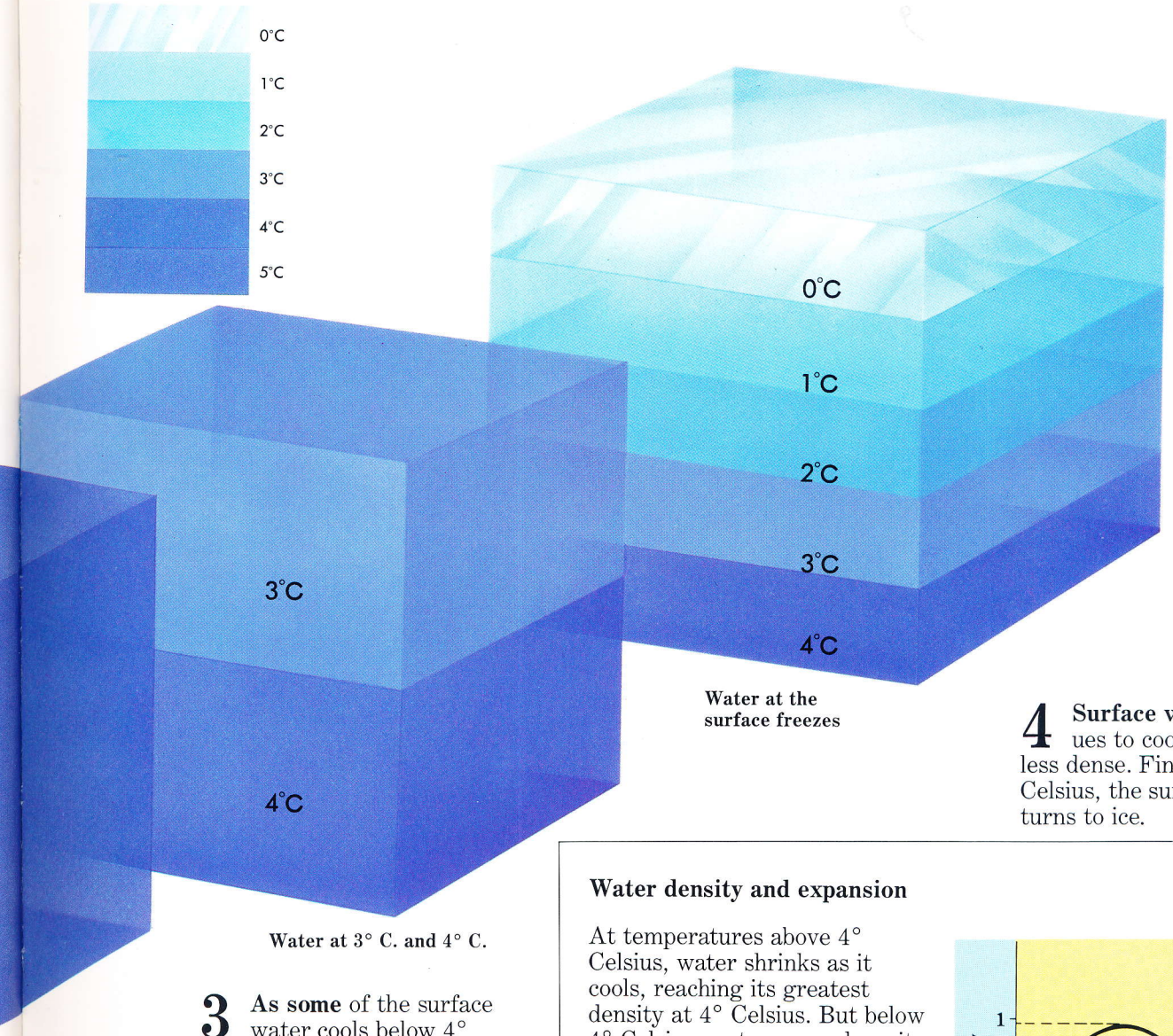
Most liquids contract as they cool, shrinking in volume and growing denser. Solid candle wax, for example, sinks to the bottom of a pan of hotter, melted wax. Water contracts, too, but only until it reaches 4° Celsius. Below that temperature, water begins to expand and its density drops. Ice is therefore lighter than near-freezing water, and as a result, it floats.

How water freezes



1 Pond water cooling to 4° Celsius becomes denser and sinks. Warmer, lighter water rises to the surface, then cools and sinks.

2 As the last bit of water reaches 4° Celsius, convection—in which cold water sinks and warmer water rises—stops. Now all the water is the same temperature. Its density, too, is uniform.



Water at the surface freezes

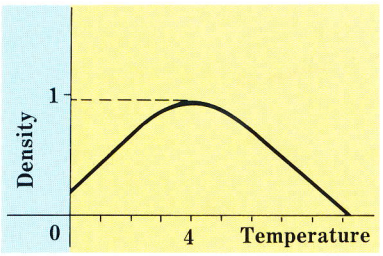
4 **Surface water** continues to cool and to grow less dense. Finally, at 0° Celsius, the surface water turns to ice.

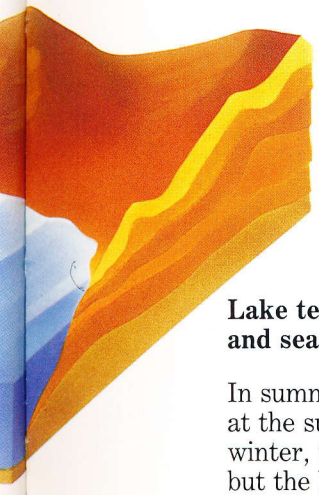
Water at 3° C. and 4° C.

3 **As some** of the surface water cools below 4° Celsius, it expands and becomes less dense. Since the water at 3° Celsius is lighter than at 4° Celsius, the cooler water stays on top.

Water density and expansion

At temperatures above 4° Celsius, water shrinks as it cools, reaching its greatest density at 4° Celsius. But below 4° Celsius, water expands as it cools further and its density falls. This density is measured in terms of mass per unit volume, or g/cm^3.



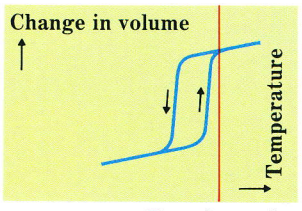


Lake temperature and seasons

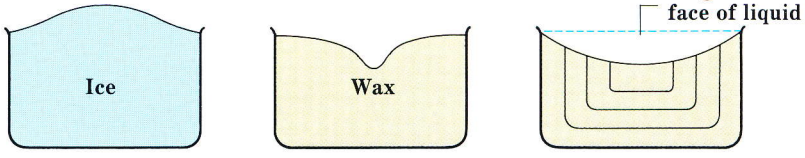
In summer, water is warmer at the surface than below. In winter, the top may freeze, but the bottom is warmer.

Wax and ice freeze differently

A bump forms on an ice cube (*below, left*) because the water at the centre, freezing last and expanding as it freezes, can only rise. But a dip forms in the top of a wax block, because wax (*below, centre*) contracts after it solidifies. Liquids that contract evenly as they freeze (*below, right*) form a curved surface.



Wax loses volume after it freezes.

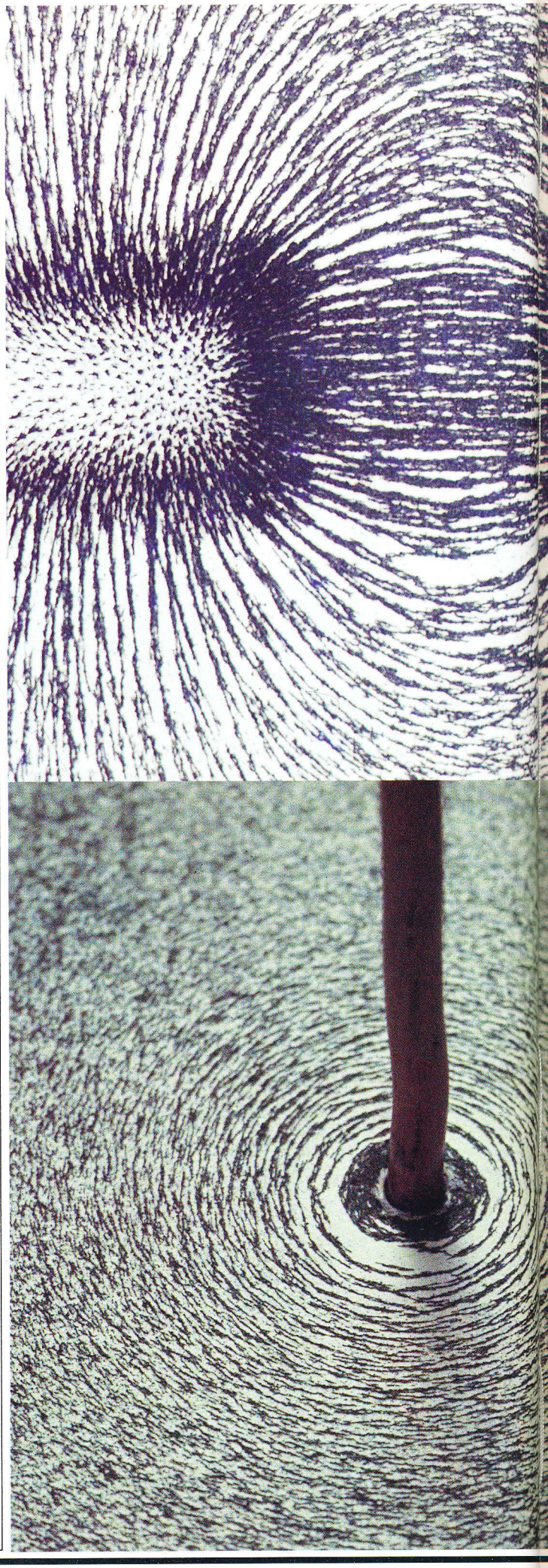


5
Electricity and magnetism

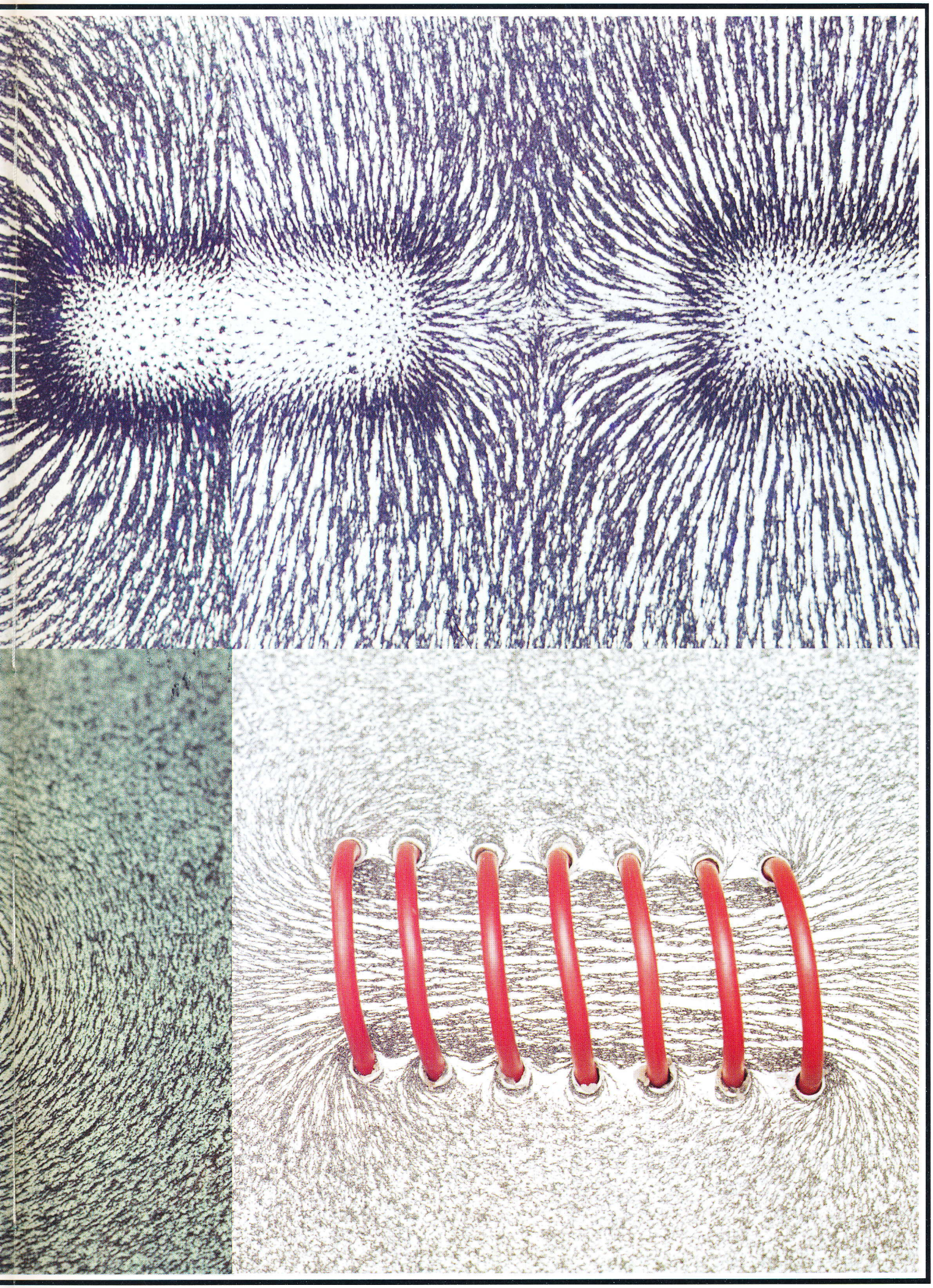
We are often not aware of electricity and magnetism, but these related phenomena are found in the most ordinary places—everywhere, in fact, that matter exists. They dwell unseen in the atoms that compose all things. The carriers of electric and magnetic forces are charged particles—the positive protons in the atom's nucleus and the negative electrons that, planetlike, orbit about those protons.

These particles are governed by a natural law, according to which opposite charges attract and like charges repel. Electricity and magnetism are both expressions of this fundamental principle. When a cat's fur sticks to the hand stroking it, static electricity —caused by a build-up of opposite charges— is to blame. When a lamp lights up, electrons flowing through a wire toward a positive charge carry the necessary energy.

Scientists have found many ways to harness electric and magnetic forces. Arising from the electric and magnetic processes found in atoms, these forces appear in various forms of energy, including current electricity and electromagnetic waves. This chapter will explore the origins and behaviour of electricity and magnetism, and look at some of the ways scientists use to measure and manage these remarkable forces.



Iron filings trace the lines of magnetic force around (*anticlockwise from top*) bar magnets, an electrified wire, and a metal coil carrying electric current. The images dramatize the intimate link between the forces of electricity and magnetism.



How can plastic attract paper?

Sometimes, common objects display seemingly extraordinary powers: A plastic rod may attract paper the way that a magnet attracts iron or the way Styrofoam clings to other objects. Such unusual effects are caused by static electricity.

Static electricity results from interactions between electrically charged particles—the negative electrons and the positive protons of atoms. Normally, objects are in a balanced electrical state, since they consist of an equal number of evenly distributed negative and positive particles. If they gain or lose electrons, however, these neutral objects can become charged.

Objects become charged through friction, or rubbing, which robs some substances of a portion of their electrons, leaving them with a positive charge. For example, rubbing a plastic rod across fur transfers electrons from the fur to the plastic. The plastic then has a negative charge and the fur a positive charge. If the negatively charged plastic is then brought near electrically balanced scraps of paper, the paper sticks to the plastic. The "magnetic" hold is caused by the build-up of a negative charge in the plastic.

Electricity's cardinal rule

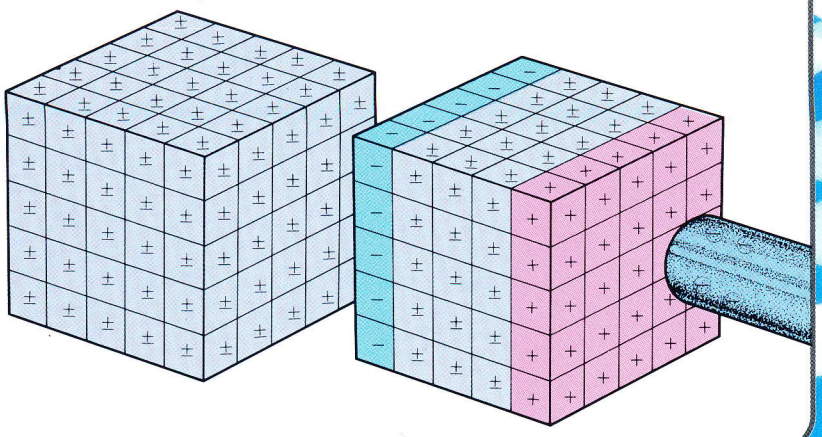
A fundamental law of electricity states that opposite charges (+ −) attract each other, while identical charges (+ + or − −) repel. The strength of these forces depends on distance: The closer the charged objects are to each other, the stronger the force.

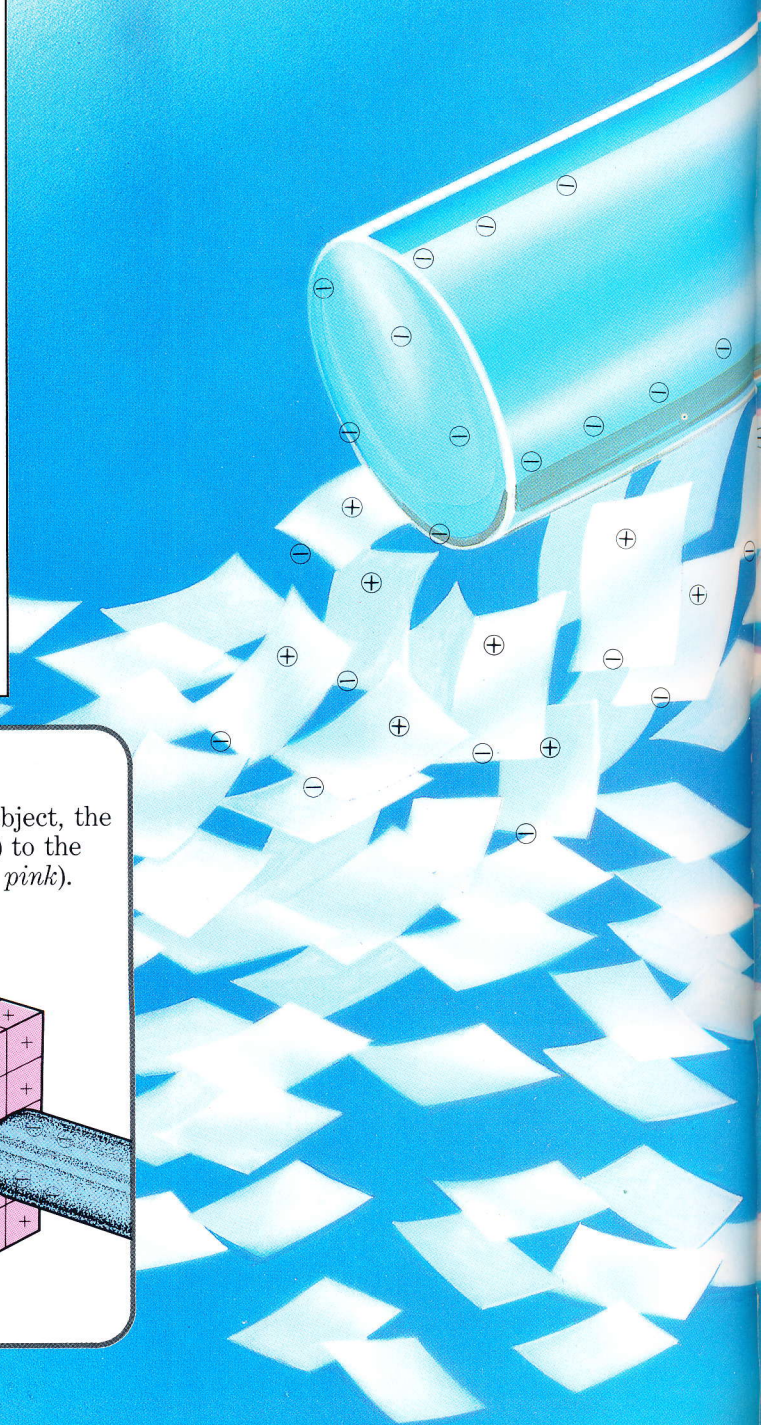
Attraction of opposite electrical charges

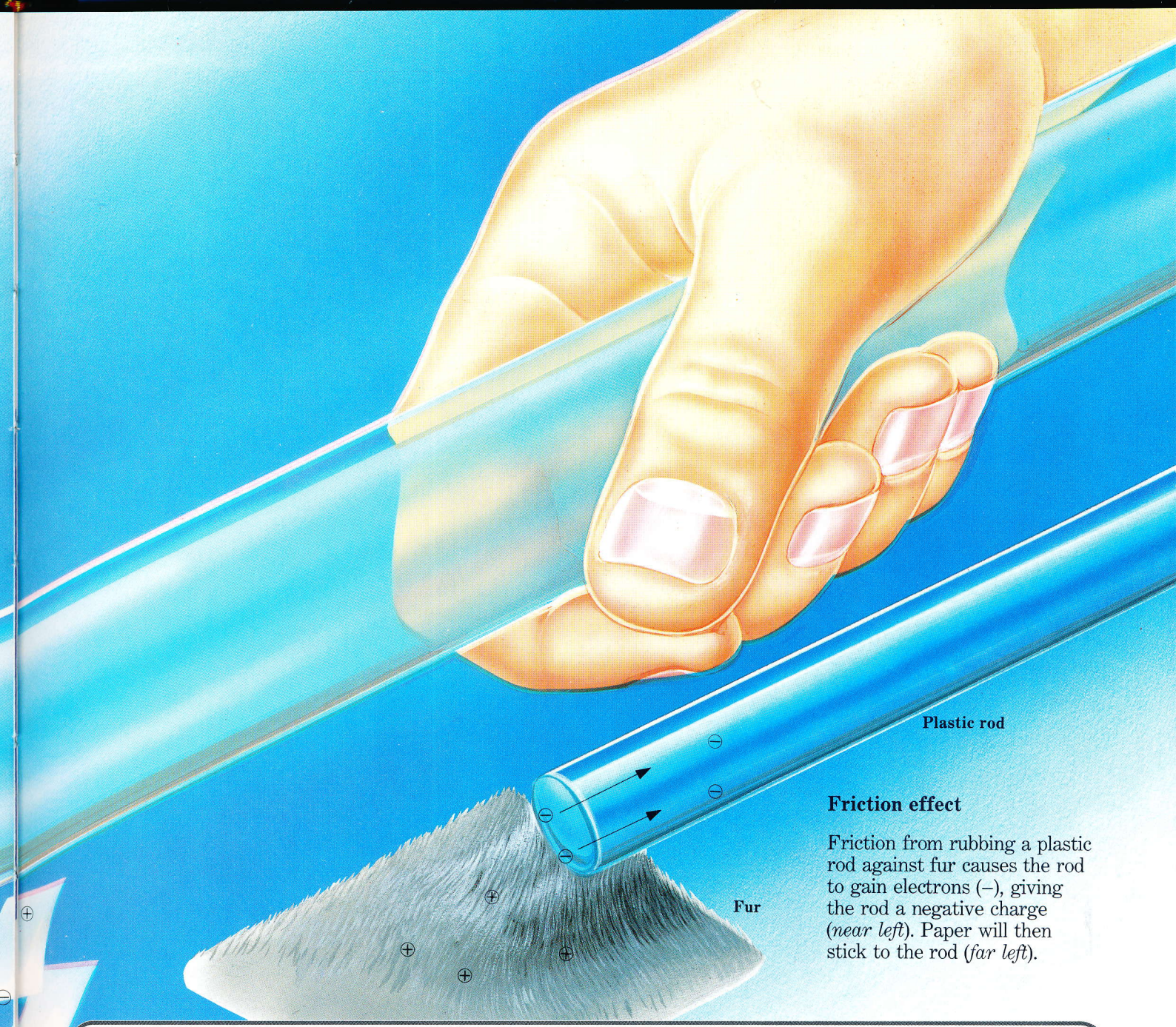
Repulsion of like electrical charges

Charge without touch

If a negatively charged wand is held next to a neutral object, the charge will drive surface electrons in the object (–, *blue*) to the far side. The object's near side will become positive (+, *pink*).





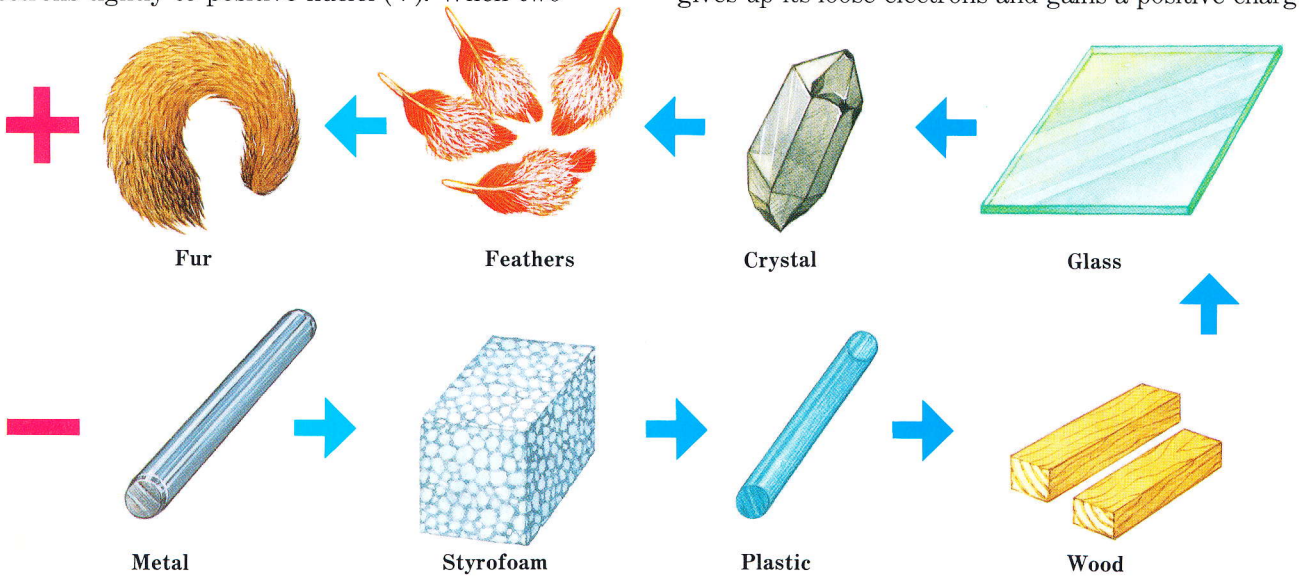


Friction effect

Friction from rubbing a plastic rod against fur causes the rod to gain electrons (–), giving the rod a negative charge (*near left*). Paper will then stick to the rod (*far left*).

Determining charge

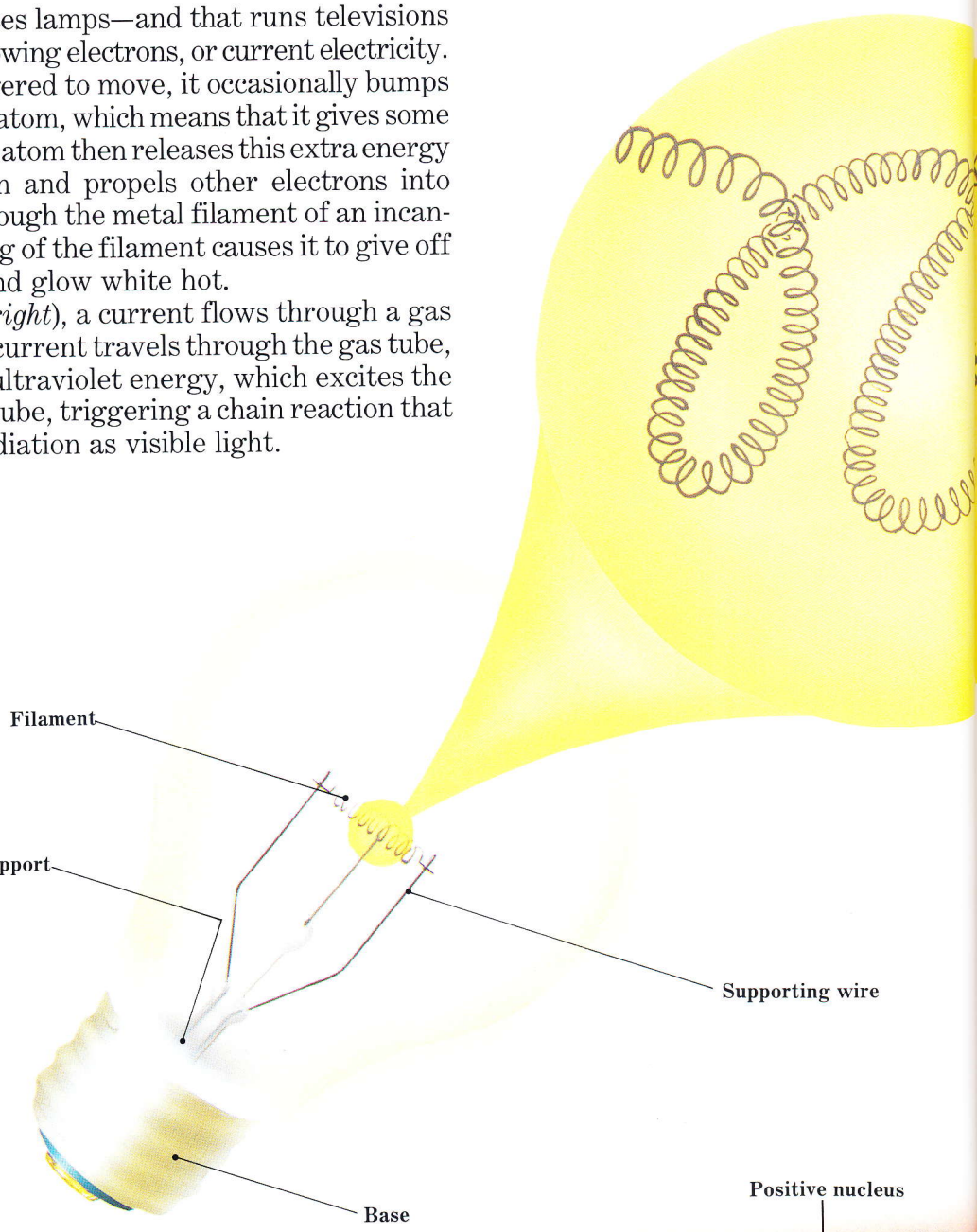
Certain materials have more "free" electrons that are held loosely to individual atoms (–). Others bind their electrons tightly to positive nuclei (+). When two materials such as Styrofoam and feathers are rubbed together, the one with more free electrons, feathers, gives up its loose electrons and gains a positive charge.



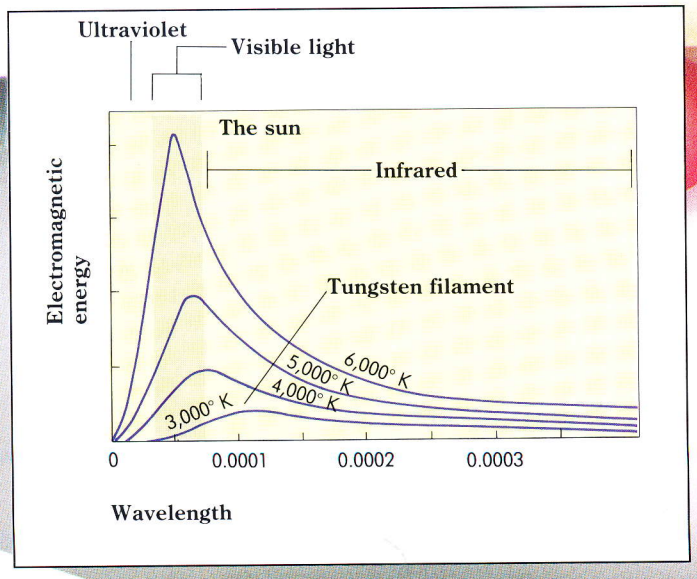
How does a light bulb glow?

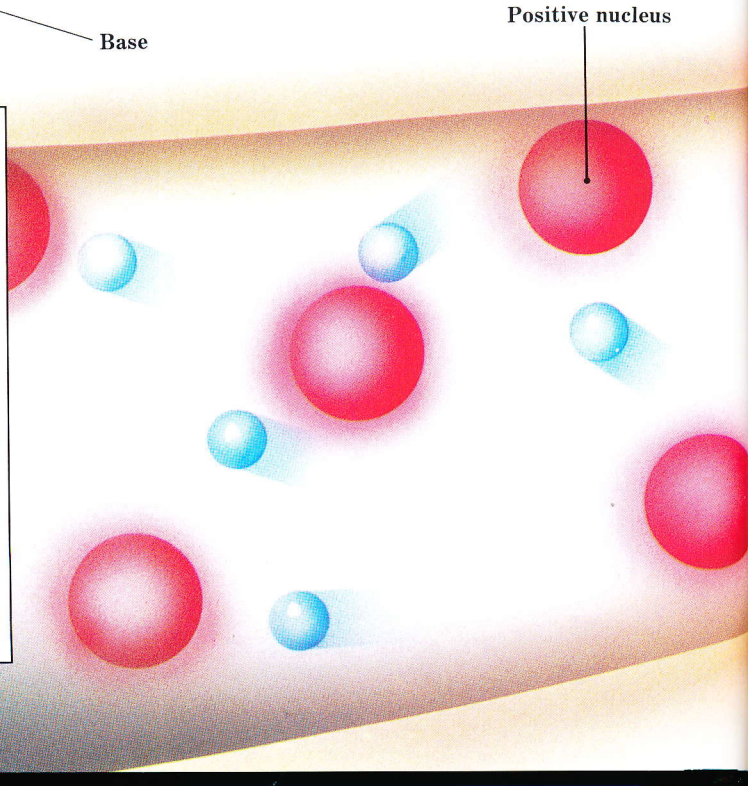
The electricity that illuminates lamps—and that runs televisions and appliances—consists of flowing electrons, or current electricity. When a free electron is triggered to move, it occasionally bumps against an atom, exciting the atom, which means that it gives some of its energy to the atom. The atom then releases this extra energy as electromagnetic radiation and propels other electrons into action. As electrons flow through the metal filament of an incandescent light bulb, the heating of the filament causes it to give off electromagnetic radiation and glow white hot.

In fluorescent lamps (*far right*), a current flows through a gas instead of a filament. As the current travels through the gas tube, it causes the gas to give off ultraviolet energy, which excites the phosphor coating inside the tube, triggering a chain reaction that releases electromagnetic radiation as visible light.



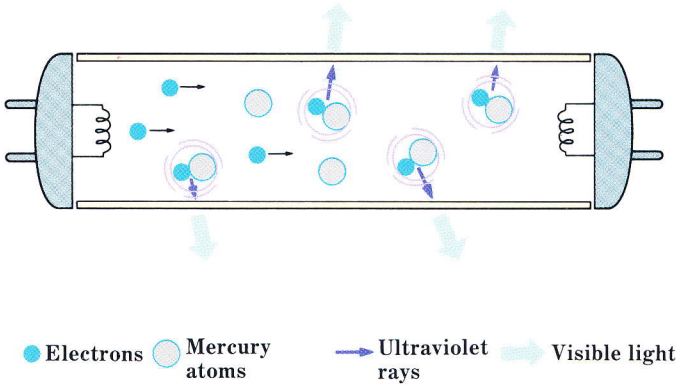
The wavelength at which hot objects emit radiation most intensely depends on the objects' temperature. The sun, at 6,000° Kelvin, emits most of its radiation as visible light, while the filament of a 100-watt light bulb, at about 3,000° Kelvin, gives off most of its energy in the infrared and only a little in the visible range.





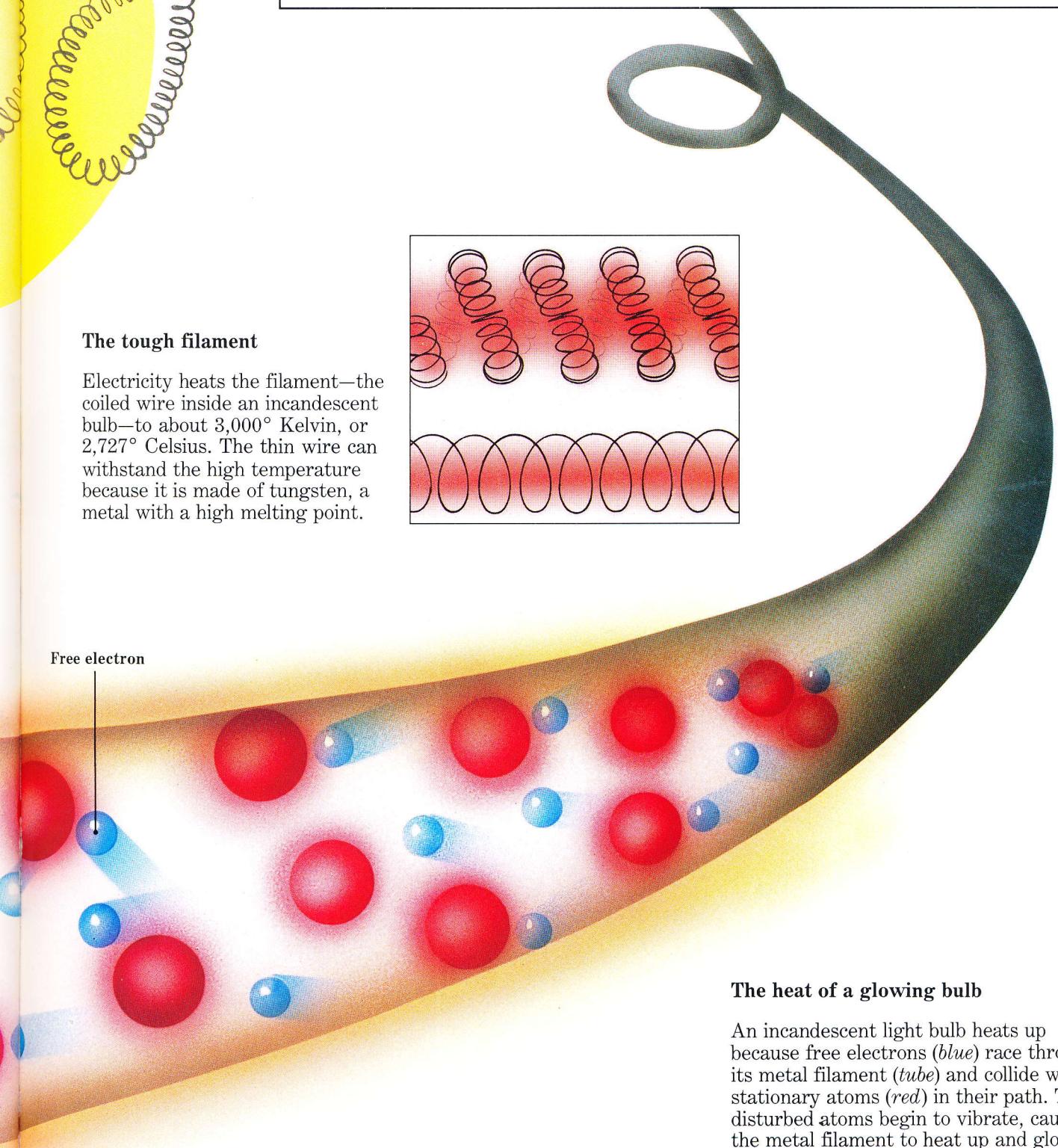
Fluorescent light from gas

Fluorescent lamps rely on electrons, gas, and a chemical called phosphor to produce light. Inside a glass tube, flowing electrons strike gas atoms, energizing them. The excited atoms release invisible ultraviolet rays, which bombard the phosphor coating of the tube. The phosphor absorbs these rays and reradiates them as visible light.



The tough filament

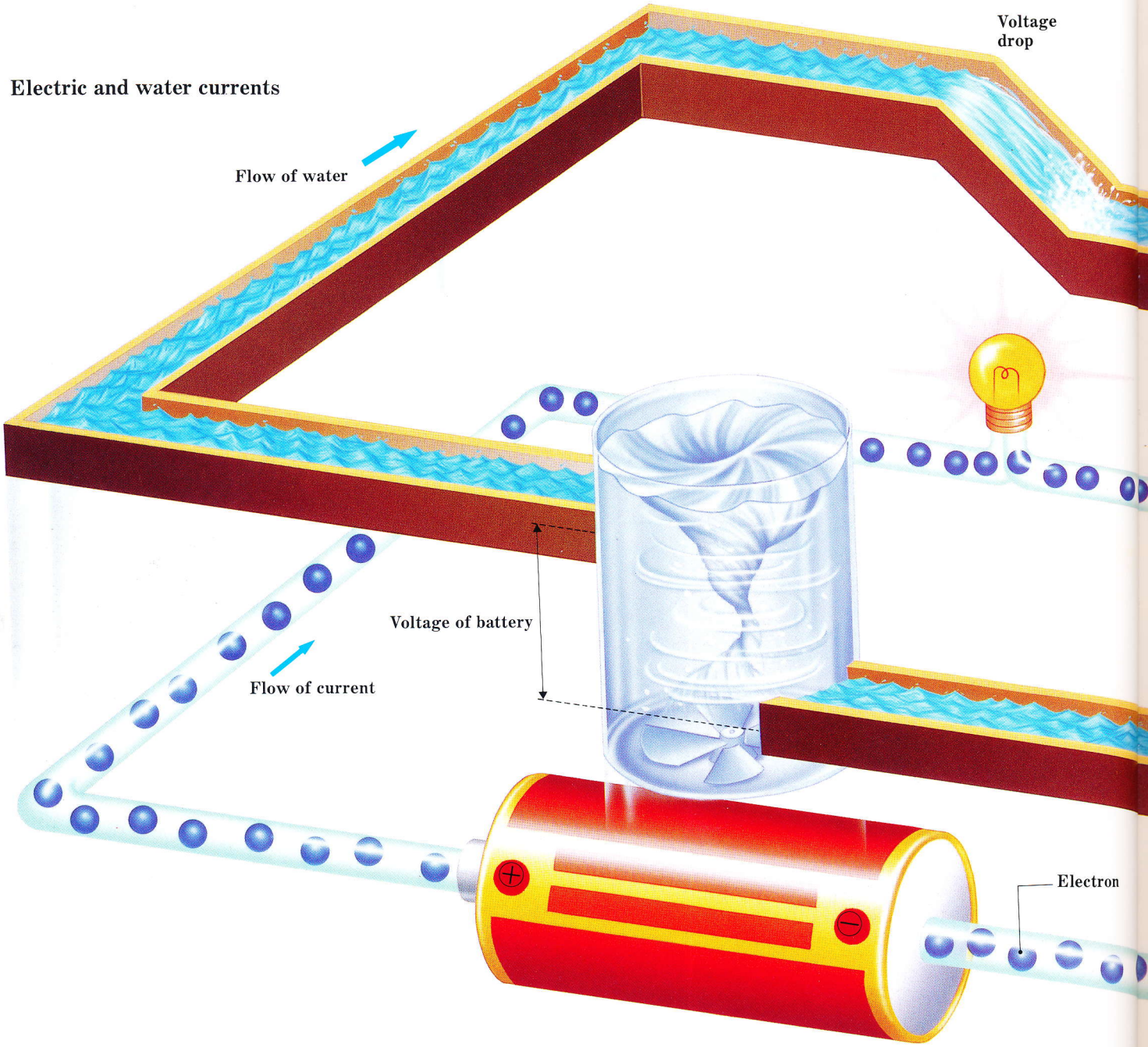
Electricity heats the filament—the coiled wire inside an incandescent bulb—to about 3,000° Kelvin, or 2,727° Celsius. The thin wire can withstand the high temperature because it is made of tungsten, a metal with a high melting point.



The heat of a glowing bulb

An incandescent light bulb heats up because free electrons (*blue*) race through its metal filament (*tube*) and collide with stationary atoms (*red*) in their path. The disturbed atoms begin to vibrate, causing the metal filament to heat up and glow.

How does electricity work?



Electric current can run machinery only when it is harnessed in a circuit. A circuit is a channel through which electricity moves. Its source is a power supply, such as a battery, to which an appliance like a lamp is connected by a power cable.

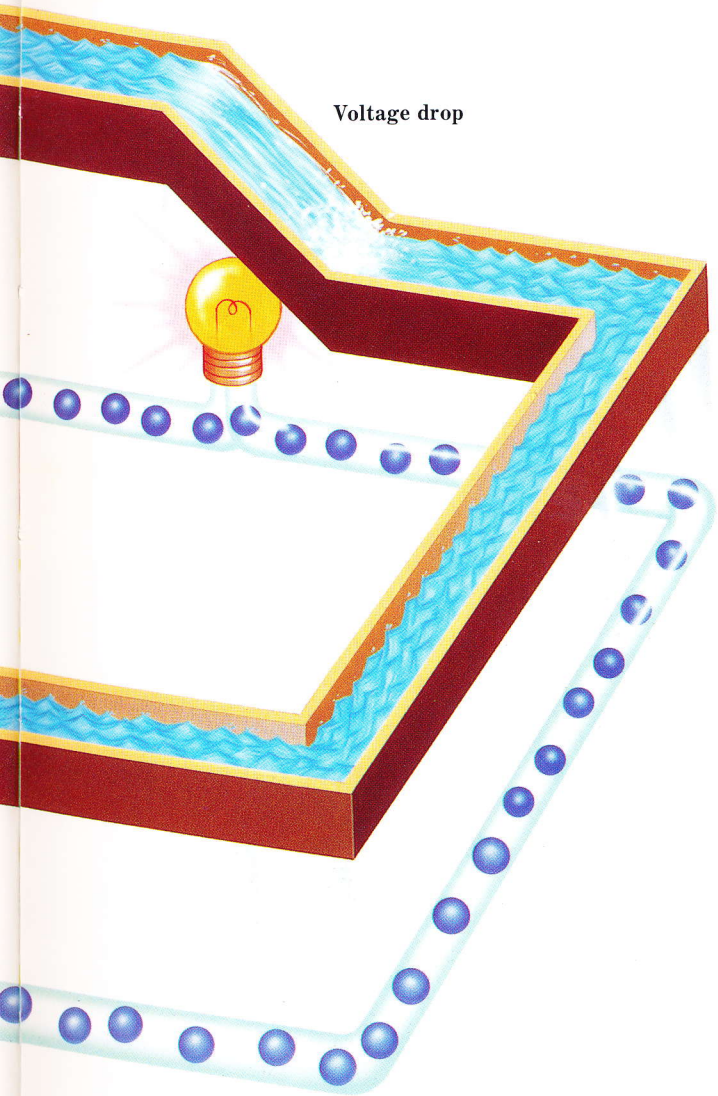
The circuit does not end in the appliance but loops back to the power source. The power that keeps the electric current flowing in a circuit is known as the electromotive force, or voltage. Because appliances retard a circuit's current they are called resistors.

Understanding the relationship between electric current, voltage, and resistance can be made easier by imagining the current as water flowing in a duct (*above*). The battery can be thought of as a water pump and the electric current as the volume of water. Representing the circuit's resistors—the two light bulbs—are two water slides in the duct.

In this model, each time the water (current) hits a slide (a resistor), it drops to a lower level (a lesser voltage). The volume of water stays the same, but its height (power) diminishes. So it is with electric current. When the current passes through a resistor, its energy is siphoned off and its voltage decreases.

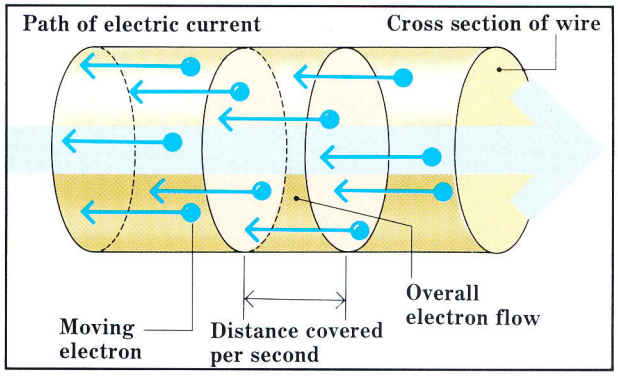
Calculating voltage drop

When electric current passes through a resistor, such as a light bulb, the pressure, or voltage, on the current decreases. This decrease is called a voltage drop. The change in voltage can be calculated mathematically by multiplying the amount of resistance by the amount of electric current.



Current and electron flow

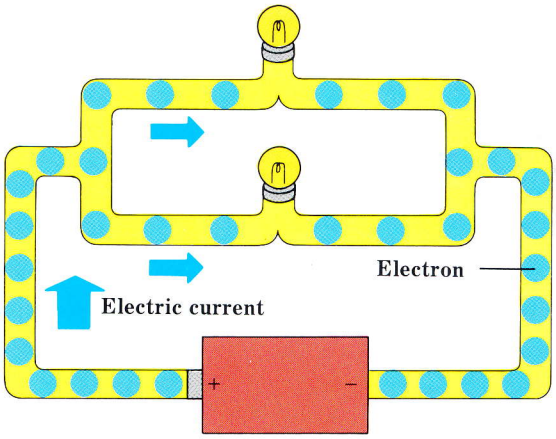
Electrons (*blue balls*) flow toward their power source's positive pole, giving rise to a current that is defined as moving from the positive pole to the negative (*large blue arrow*). How much current flows depends on the number of electrons travelling through in a set time.



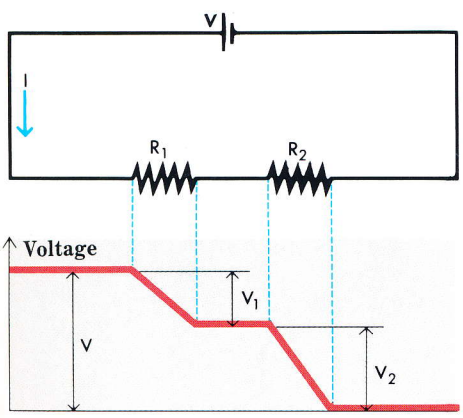
Scientists defined the direction in which current flows before they discovered electrons.

Tracing a parallel circuit

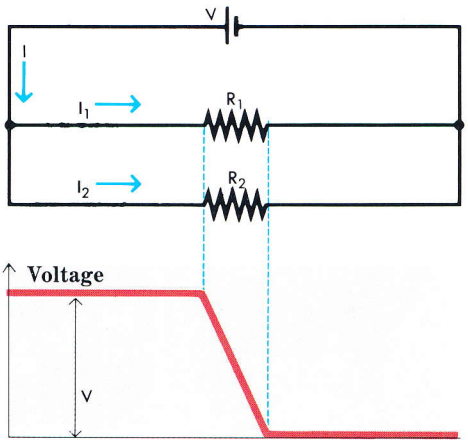
In a parallel circuit, the electric current (*blue arrows*) traces two separate paths before returning to its source (*red battery*).



Circuits and voltage



The series circuit at left includes two resistors (R), which successively decrease the voltage (V). The drop in voltage is the sum of the resistance.

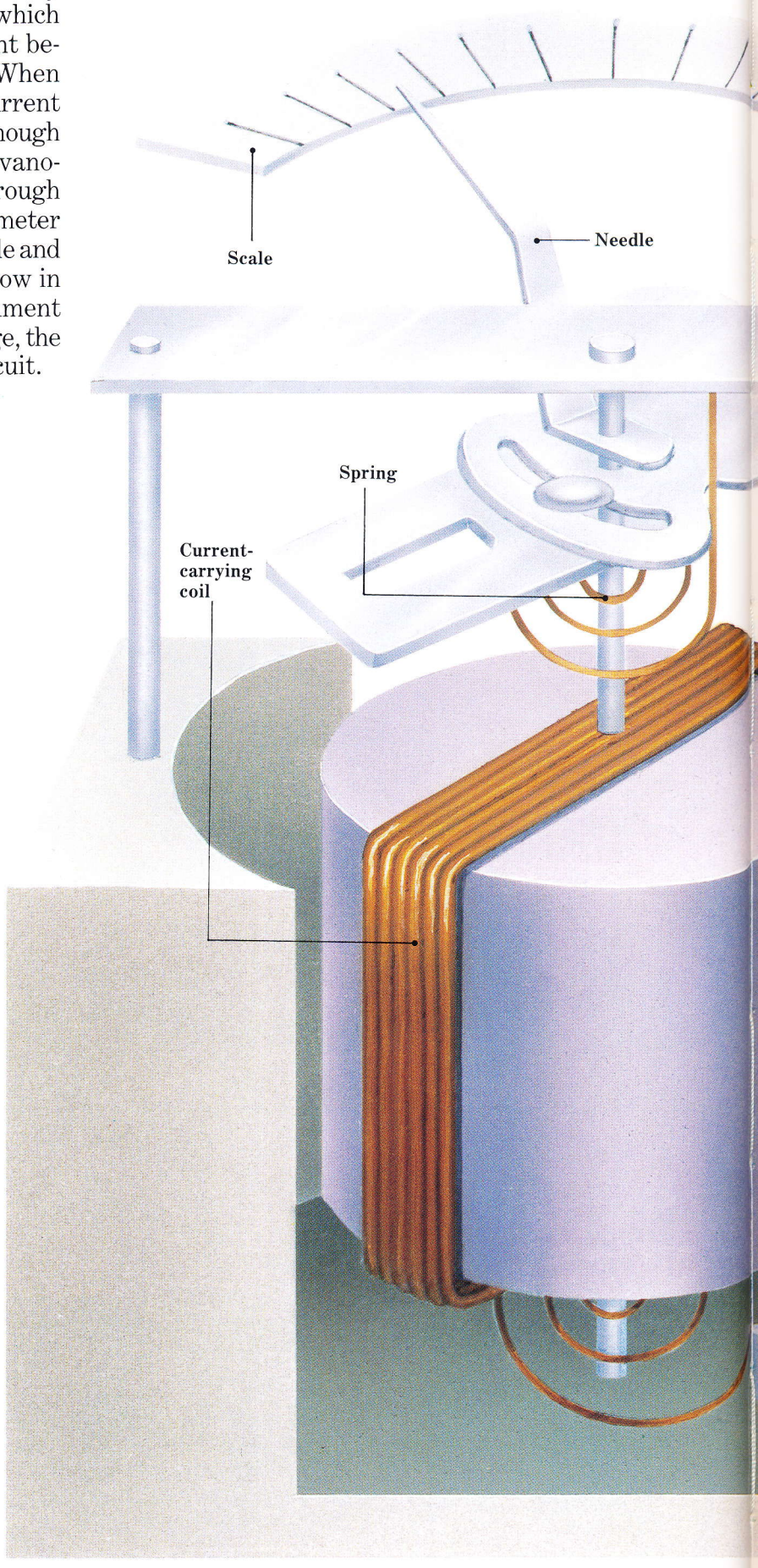


In a parallel circuit (*right*), the current travels along different paths. The positions of the resistors (R) cause a simultaneous drop in voltage.

How is electricity measured?

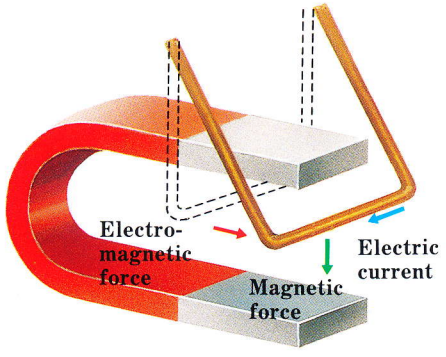
Because electricity is invisible, scientists have devised indirect ways of measuring it. One way is with the help of a galvanometer (*right*), which consists of a thin wire coil carrying current between the poles of a permanent magnet. When electricity travels along the wire coil, the current produces an electromagnetic force strong enough to move the coil past the magnet. The galvanometer gauges how much current flows through the circuit by how far the coil moves. An ammeter uses this concept with the addition of a needle and scale, which indicate the rate of current flow in amperes. By adding a resistor, the instrument becomes a voltmeter, which measures voltage, the force moving the current through the circuit.

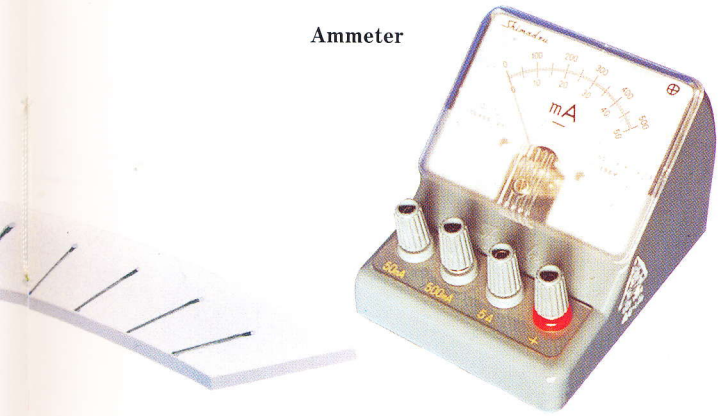
Inside an ammeter



The right-hand rule

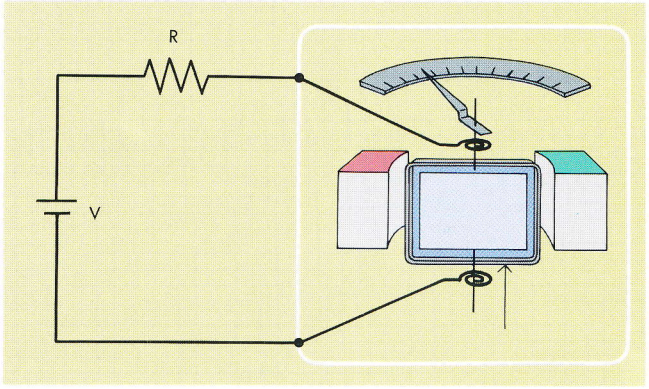
When a current-carrying wire is in the magnetic field—the region of magnetic influence—of a permanent magnet, the combined energy of the current and the magnetic field produces an electromagnetic force strong enough to move the wire. To remember the relationship between the direction of the current, the force, and the magnetic field, physics students created a memory device called the right-hand rule. If one extends the thumb of one's right hand, the thumb indicates the direction of current flow; the fingers point in the direction of the external magnetic field; the palm faces the direction of the electromagnetic force.

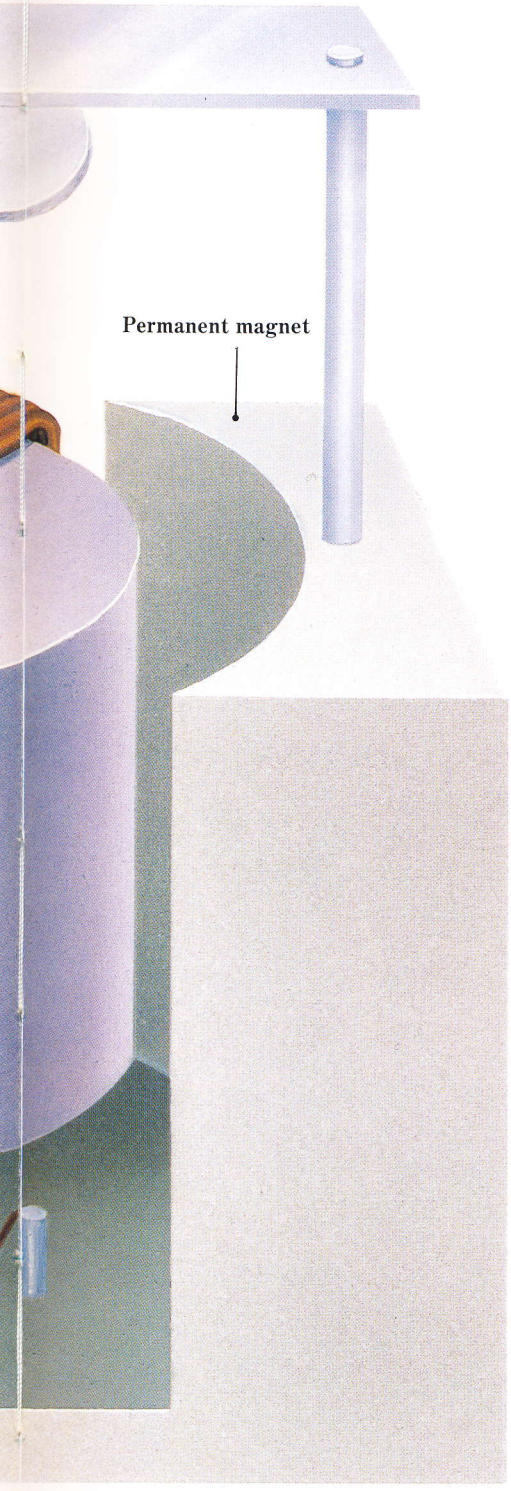




How an ammeter works

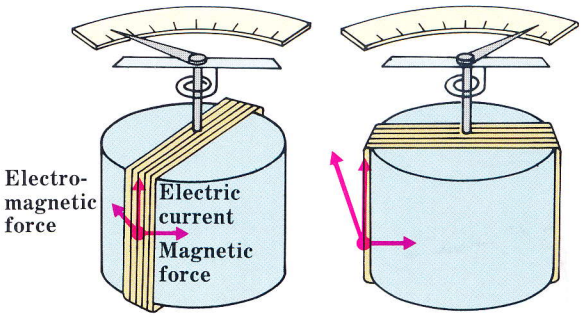
When an ammeter is connected to a circuit, the electricity generates an electromagnetic force that converts the meter's coil into a bar magnet. The permanent magnet (*pink/green boxes*) causes the bar magnet to align its north pole with the permanent magnet's south pole. A needle indicates the level of the current.





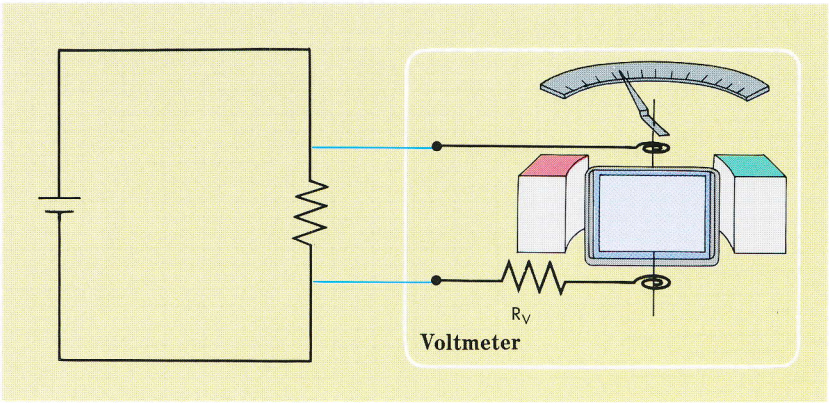
Measuring current

The electromagnetic force, generated in the coil of the ammeter, acts at right angles to the magnetic field of the permanent magnet. Since the amount of current determines the size of the electromagnetic force, which affects the deflection of the needle, the ammeter can measure current. The stronger the current (*far right*), the higher the reading.



Making a voltmeter

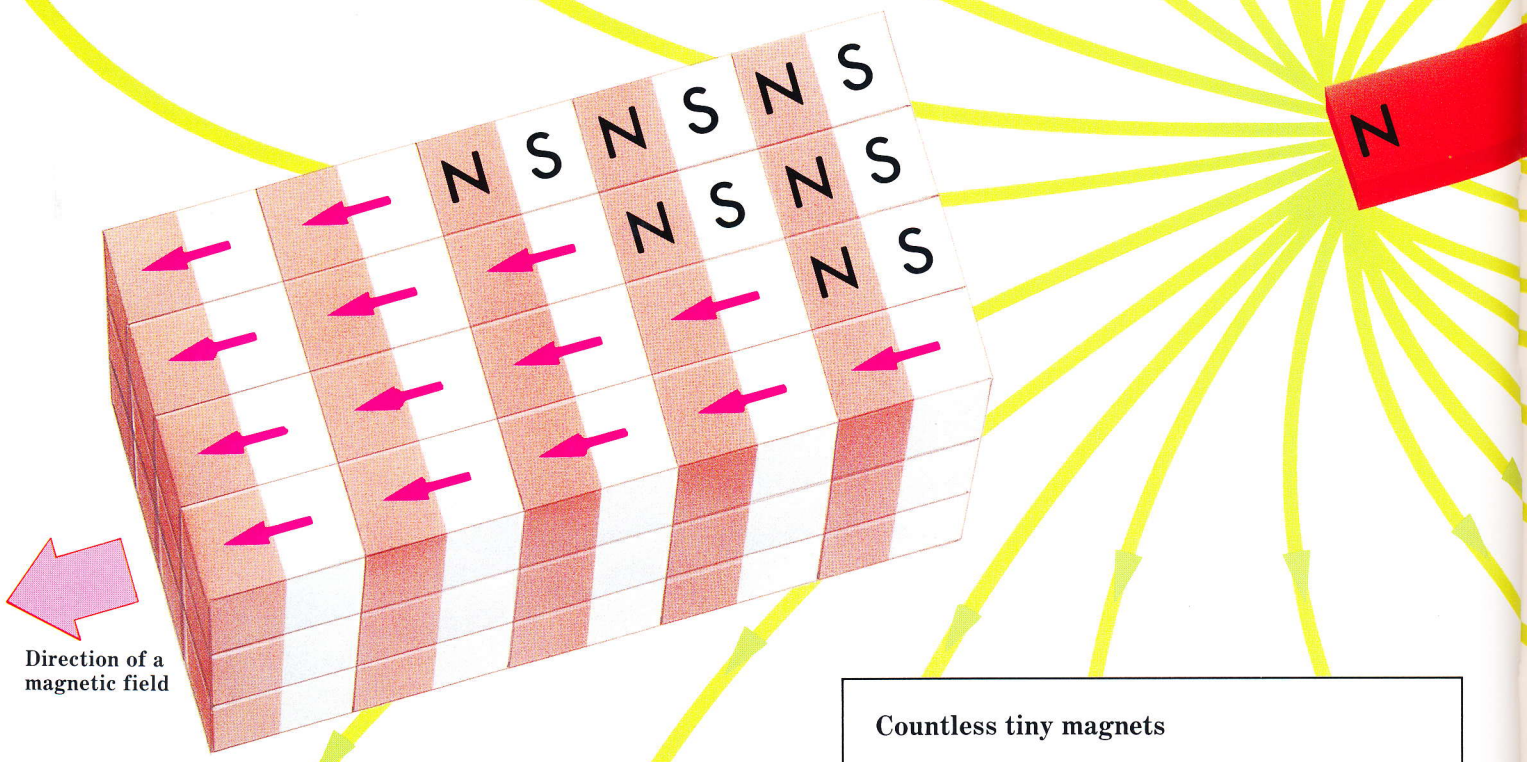
If an ammeter is connected to a resistor (R_V)—an object that slows the flow of electricity—then to a circuit, the instrument measures the voltage in the electric circuit. Voltage indicates the amount of force that is moving the current through a circuit.



Why does a magnet attract iron?

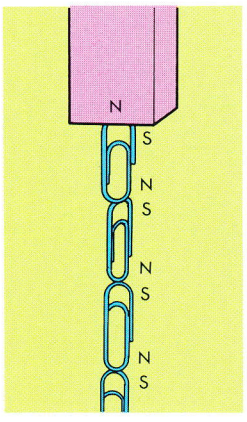
For no obvious reason, a magnet can attract certain metallic objects. Its power actually comes from the special way its electrons behave. Since an electron spinning about an atom generates a magnetic field, all atoms are tiny magnets; but in most substances, the atoms' haphazard magnetic effects cancel each other out.

In magnets, however, the atoms' magnetic fields line up in such a way that they create regions called domains. These fields have a north and a south pole. So-called field lines (*green lines*)—concentrated regions of magnetism—run from a magnet's north pole to its south pole. This is known as the field direction. A magnet's north pole will attract another's south pole, while two identical poles will repel each other. Magnets attract only certain metals, chiefly iron, nickel, and cobalt, known as ferromagnetic materials. Though these materials are not natural magnets, their atoms rearrange themselves near a magnet so that they acquire magnetic poles.



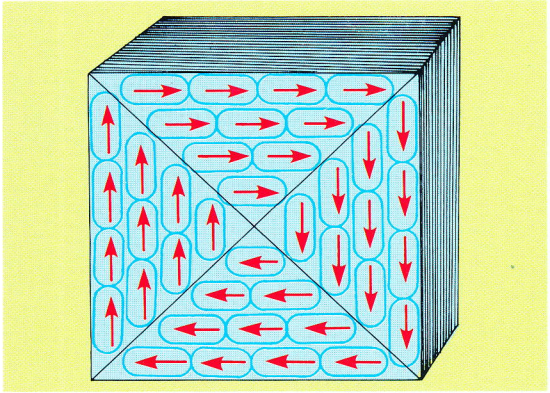
A magnetic chain

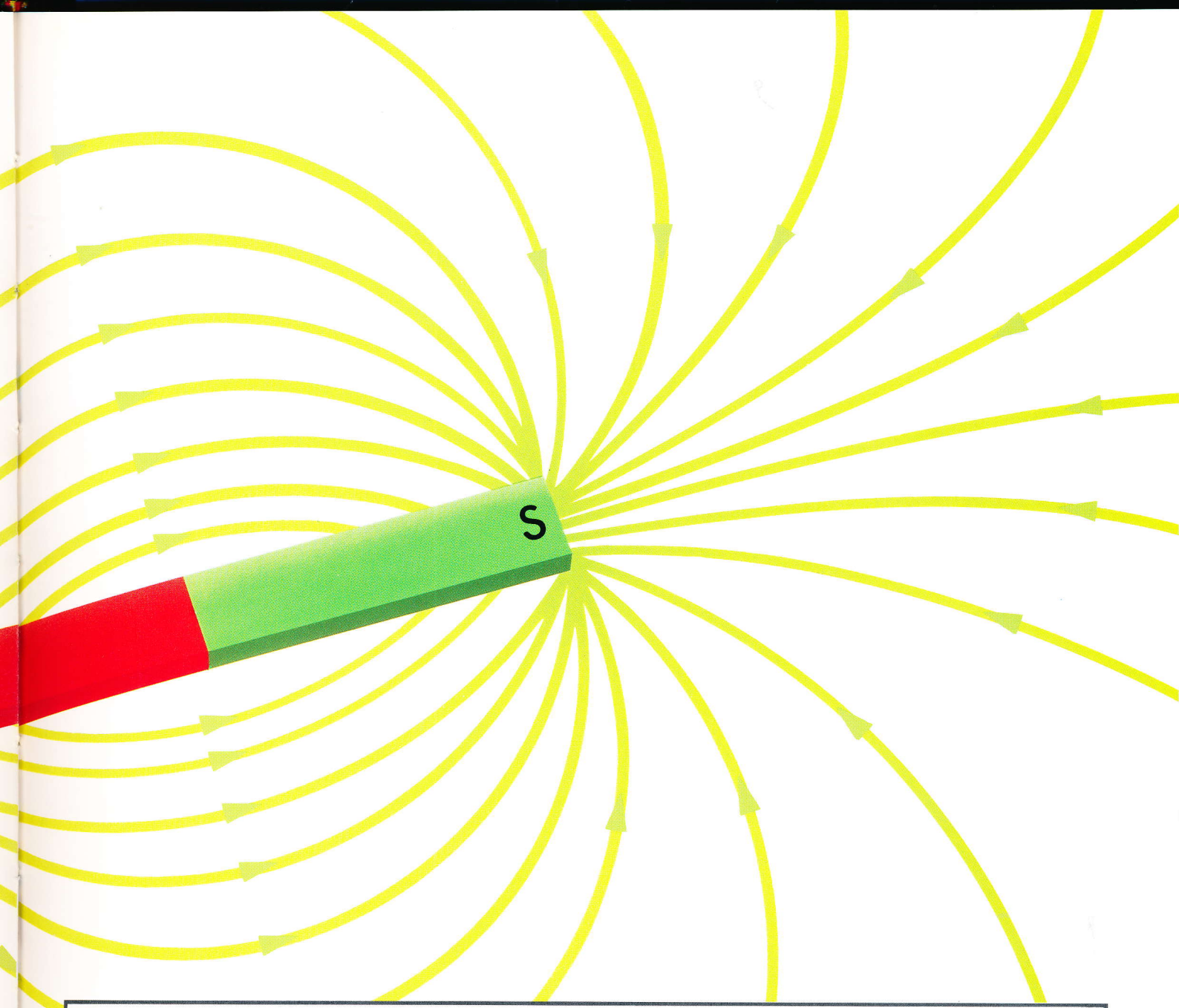
Touching the end of a magnet to metal paper clips causes each clip to develop north and south poles. The clips' poles point in the same direction as the magnet's. Each paper clip has become a magnet.



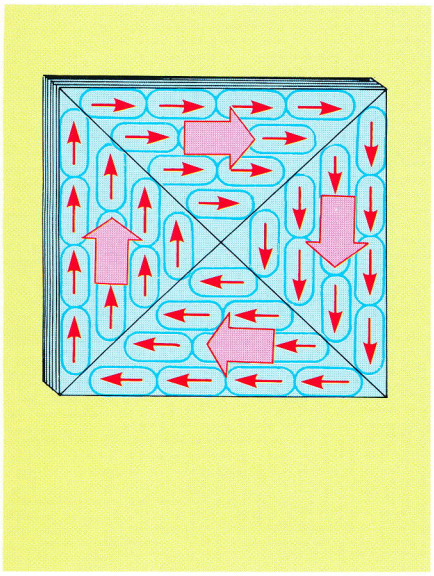
Countless tiny magnets

Some metals have a crystal structure of atoms grouped in magnetic domains. The domains' magnetic poles normally point in different directions (*red arrows*) and do not act as magnets.

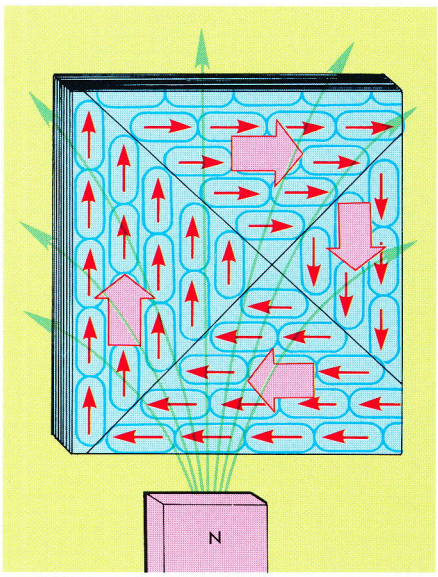




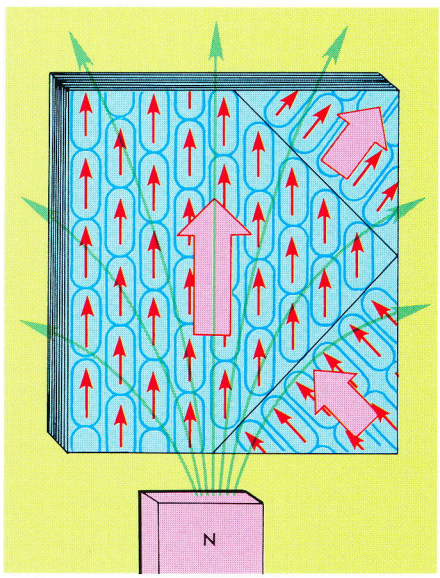
Creating a permanent magnet



1. Typically, iron's magnetic domains are randomly oriented (*pink arrows*). This neutralizes the natural magnetism in the metal.



2. When a magnet (*pink bar*) is brought near, the iron's magnetic domains begin to align with the magnet's field (*green lines*).

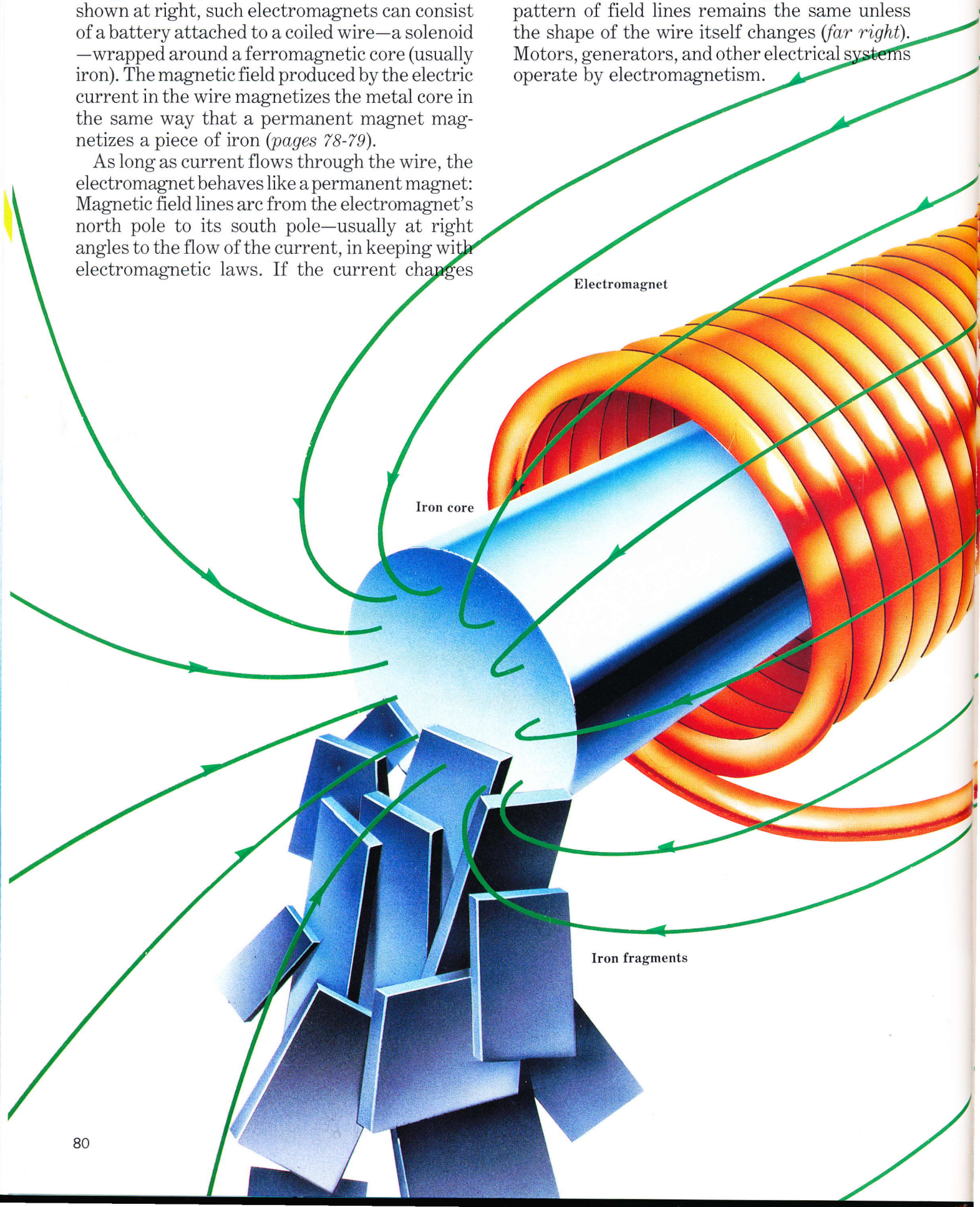


3. Once all domains line up with the magnet's field, the iron becomes a permanent magnet. It retains its power when the magnet is removed.

How can electricity make a magnet?

The discovery that electric currents generate magnetic fields led scientists to develop a magnet using electricity that can be turned on and off. As shown at right, such electromagnets can consist of a battery attached to a coiled wire—a solenoid—wrapped around a ferromagnetic core (usually iron). The magnetic field produced by the electric current in the wire magnetizes the metal core in the same way that a permanent magnet magnetizes a piece of iron (*pages 78-79*).

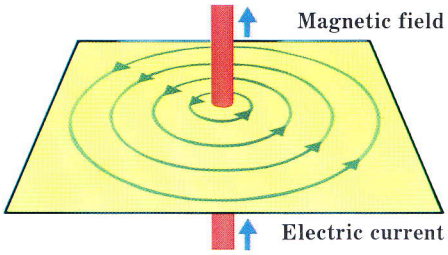
As long as current flows through the wire, the electromagnet behaves like a permanent magnet: Magnetic field lines arc from the electromagnet's north pole to its south pole—usually at right angles to the flow of the current, in keeping with electromagnetic laws. If the current changes direction, the magnet's poles flip and the field lines reverse as well. The overall shape of the magnetic field does not change, however. The pattern of field lines remains the same unless the shape of the wire itself changes (*far right*). Motors, generators, and other electrical systems operate by electromagnetism.



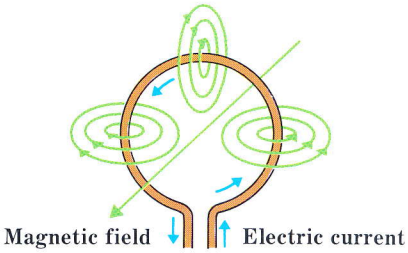
Magnetic field lines

Battery

The shape of magnetic fields



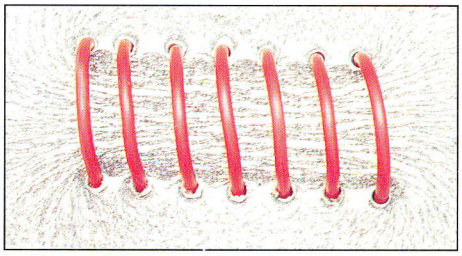
An electric current flowing upward in a straight line produces concentric rings of a magnetic field that travel anticlockwise. Reversing the current makes the field run clockwise.

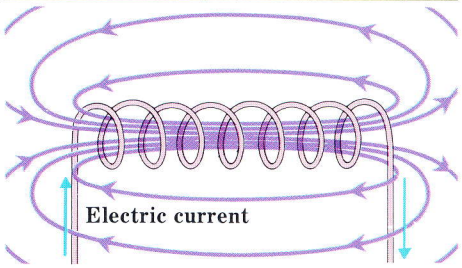


A single electrified coil with an anticlockwise current generates magnetic field lines that run directly through the coil's open centre, then up and back, forming circles.

Magnetic field and many coils

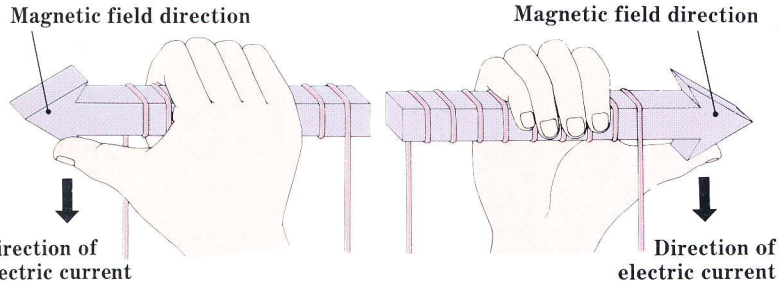
Each loop in a length of coiled, electrified wire (a solenoid) behaves like a single coil (*below*). The pattern of a magnetic field surrounding the solenoid itself is a combination of all the individual fields created by the loops.





Finding field directions

To determine the direction of magnetic field lines around a coiled electrified wire, physicists imagine gripping the wire in the direction of the electric current with the right hand. An extended thumb points in the direction of the magnetic field.

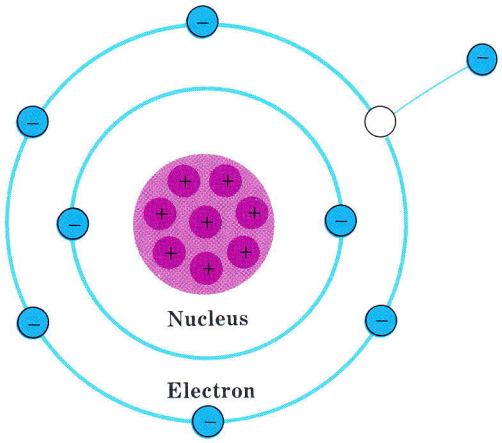


What allows electricity to flow?

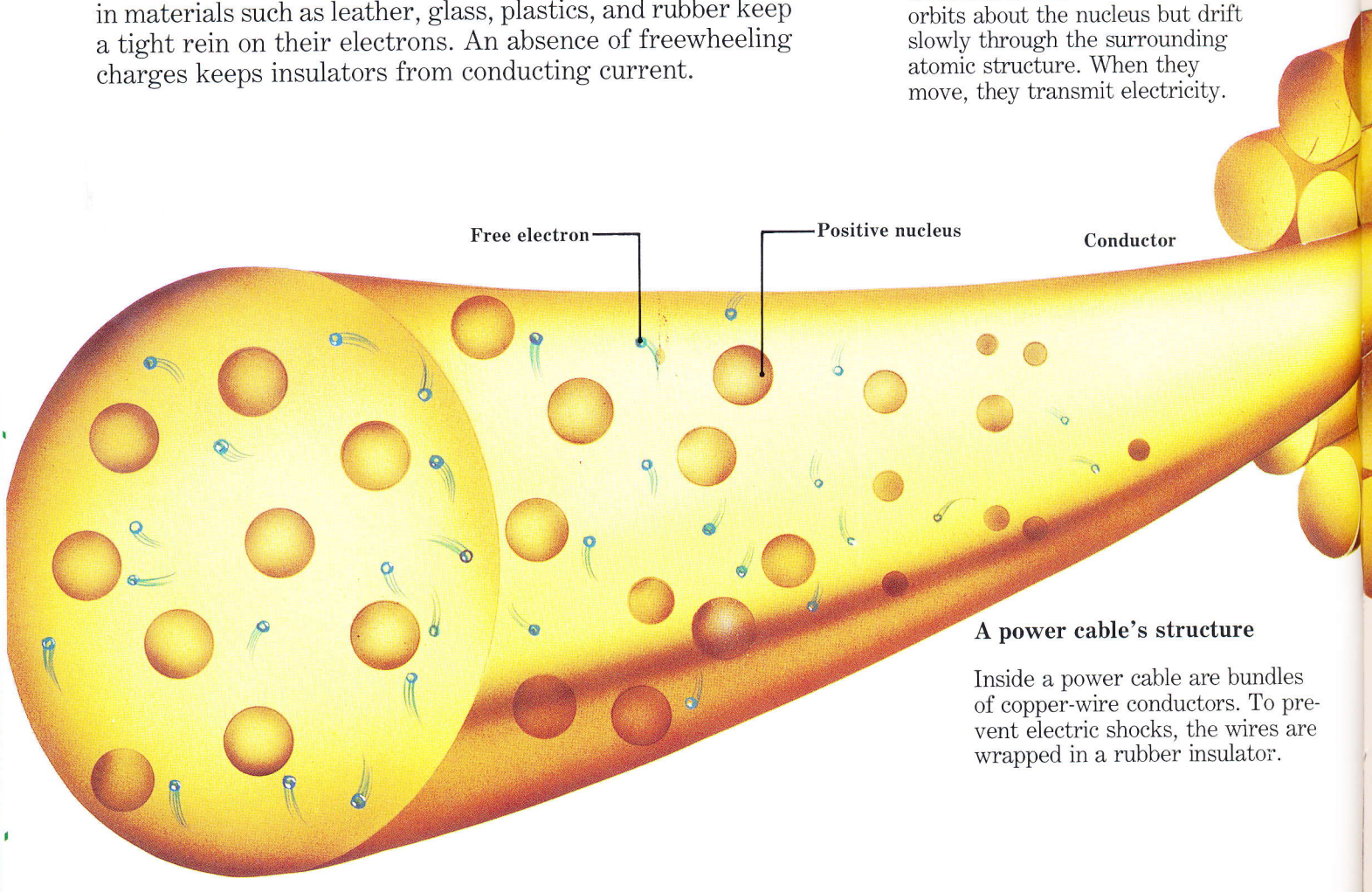
Electricity flashes through copper wire but halts when it bumps up against rubber tubing. Such examples abound in nature—certain substances are good conductors, while others block even the strongest electric current. Whether a material transmits electricity is dictated by the material's atomic structure. How easily a material channels electricity depends on how freely electrons move through it.

Conductors—chiefly metals such as iron, nickel, silver, and copper—have "loose", or free, electrons. Not attached to any particular atom, these free electrons roam through their atomic neighbourhoods, orbiting first one atom and then another. When a conductor is connected to a battery, the electric field organizes the electrons' aimless motions into a steady flow. For this reason, metals are excellent carriers of electricity.

Insulators, however, have few, if any, free electrons. Atoms in materials such as leather, glass, plastics, and rubber keep a tight rein on their electrons. An absence of freewheeling charges keeps insulators from conducting current.



Atoms of conductors have one or more free electrons. Such electrons do not remain in fixed orbits about the nucleus but drift slowly through the surrounding atomic structure. When they move, they transmit electricity.

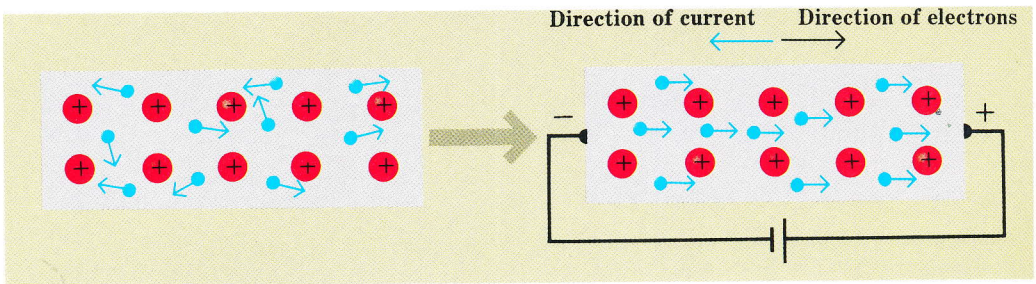


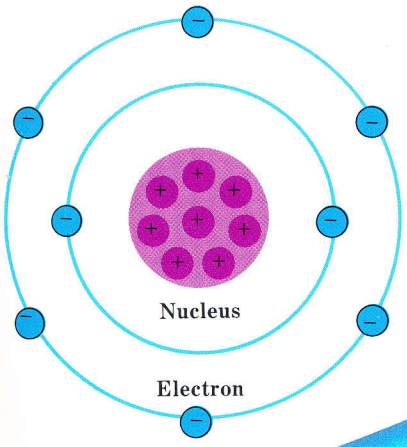
A power cable's structure

Inside a power cable are bundles of copper-wire conductors. To prevent electric shocks, the wires are wrapped in a rubber insulator.

Current in a conductor

When the conductor is attached to a battery (*far right*), electrons (*blue*) begin an orderly flow toward the battery's positive terminal, creating electric current.



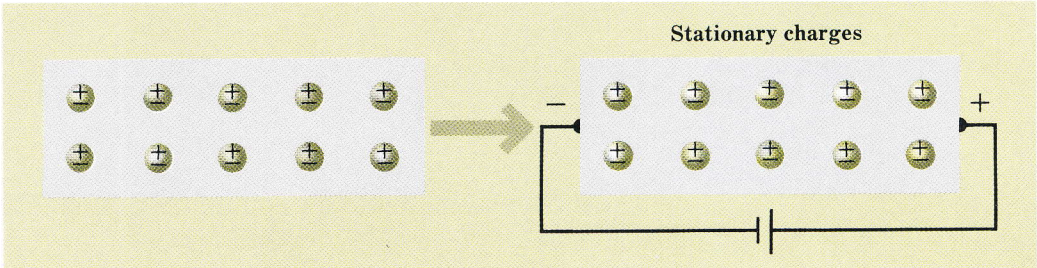


Atoms of insulators have virtually no free electrons; almost all electrons remain tightly bound to their nuclei. For this reason, insulators carry little, if any, electric current.

Insulator

The current-free insulator

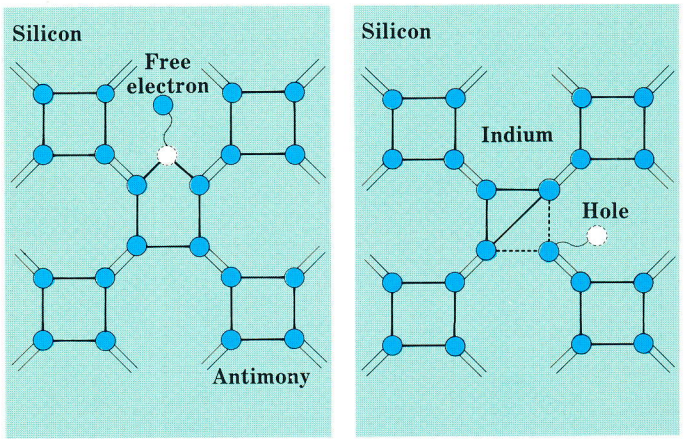
An insulator's electrons are tied to their positive nuclei. Even if the insulator is connected to a battery (*far right*), the electrons stay in place and current does not flow through.



What is a semiconductor?

A semiconductor is a crystalline material that conducts electricity but not as well as metals; it also resists electricity but not as well as many insulators. In general, semiconductors' electrons are tightly bound to their nuclei. But if a few atoms of antimony—with a surplus of electrons—are incorporated in a semiconductor such as silicon, the free electrons give it a negative charge. By replacing a few atoms with indium, which has room for extra electrons, the semiconductor has holes where electrons should be; the holes relay a positive charge.

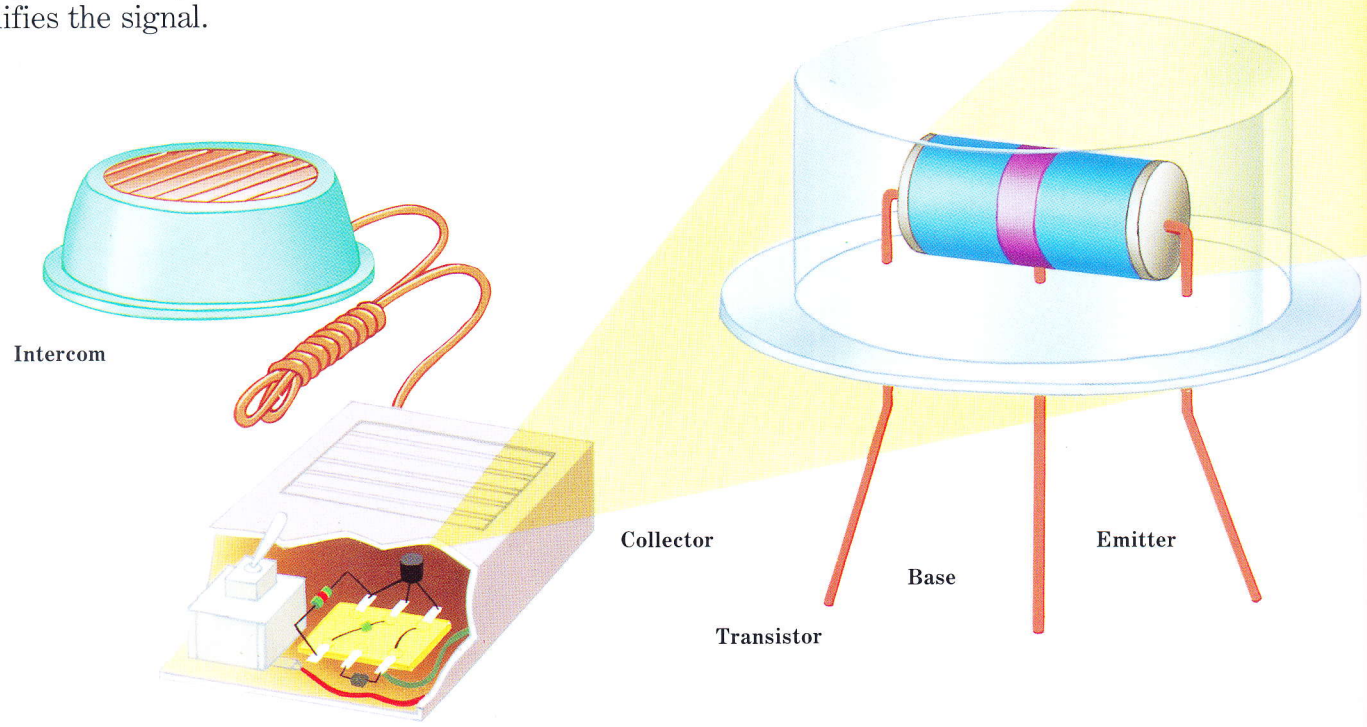
These properties make semiconductors useful in transistors to amplify current, to block current, or to let current flow in only one direction. In a typical NPN transistor (*opposite, top*), a layer of positive (P) semiconductor, the base, is sandwiched between two negative (N) layers, the emitter and the collector. When, for example, a small signal from an intercom is channelled through the base, the movement of electrons amplifies the signal.



N-type P-type

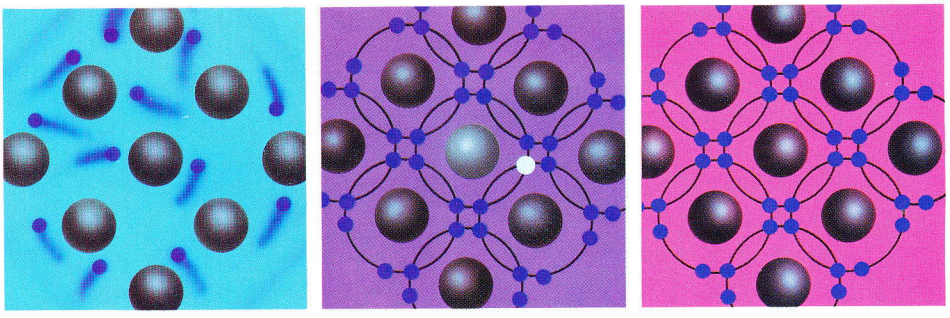
Looking into semiconductors

Negatively charged N-type semiconductors have excess electrons. Positive P-types lack electrons but have holes where electrons should be.



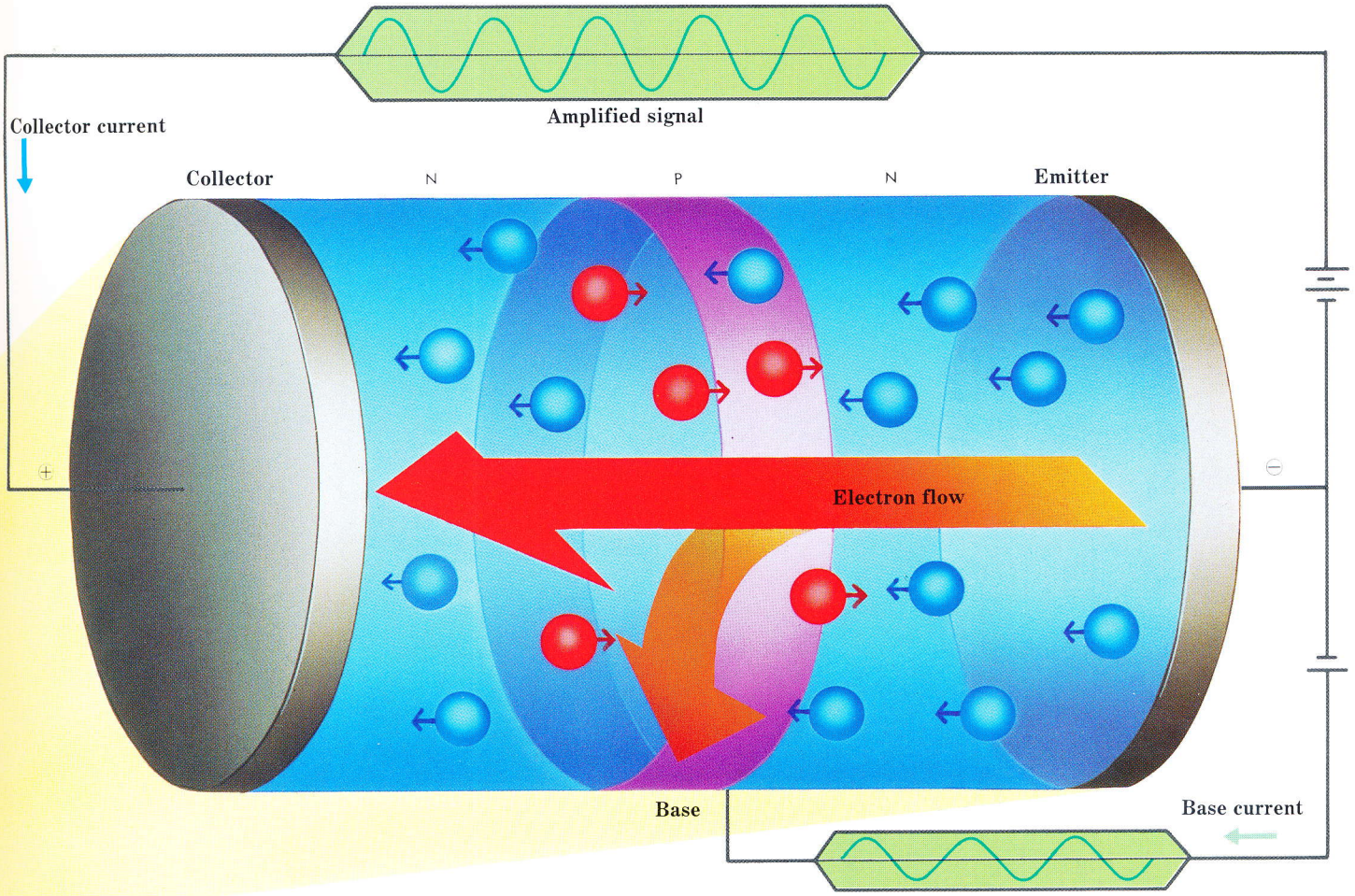
The semiconductor difference

Unlike conductors, which have many free electrons, and insulators, which have virtually none, a semiconductor has a small number of free electrons and so-called holes (*white dot*)—empty spots left by free electrons. Both holes and electrons conduct current.



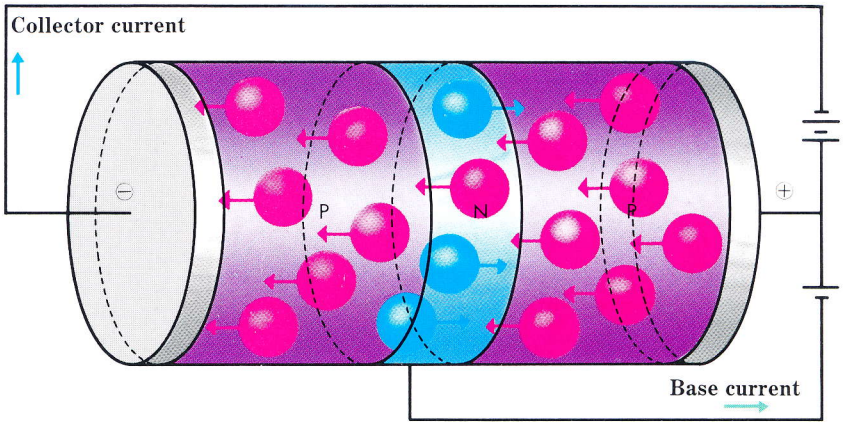
Conductor Semiconductor Insulator

The NPN transistor



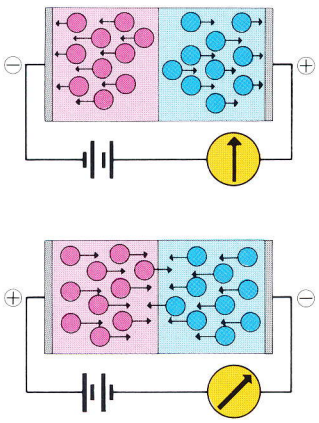
The PNP transistor

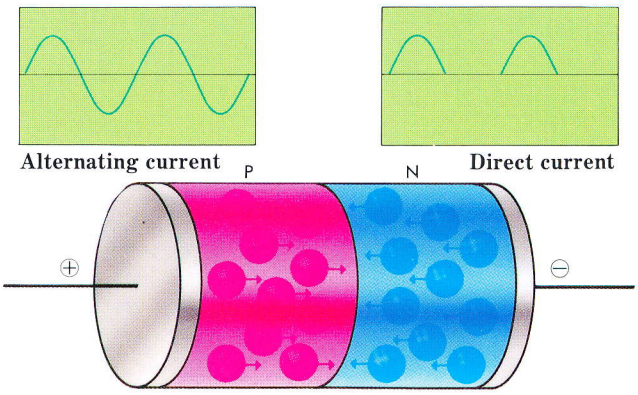
Holes move from the positive emitter (+) to the negative base (*N-layer*) and on to the positive collector at the negative terminal (–), adding to the current.



On or off

At right, top, an anticlockwise current causes negatively charged electrons (*blue*) and positively charged holes (*pink*) to move away from each other at the junction of the N-type and P-type silicon in the diode, breaking the current. At bottom, a clockwise current draws electrons and holes toward the junction, and the diode conducts current in one direction, converting AC current to DC.





The diode's signal at top left shows AC current; at top right only DC current gets through.

How is electricity sent to a home?

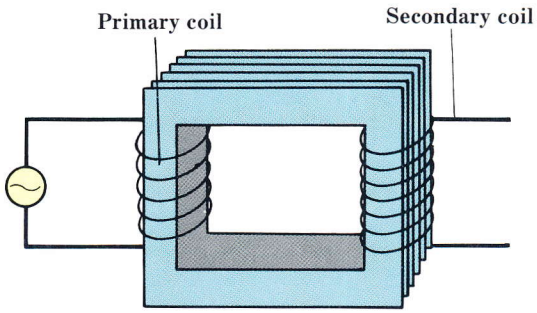
The electricity used in homes comes from large electric generating stations. These utilities transmit electricity to regional substations, which then distribute it to consumers.

Because transmission lines resist current flow, the current loses energy as heat. The amount of power lost depends on current flow. Direct current (DC) flows in one direction; alternating current (AC) regularly reverses its course. Years ago, utilities supplied DC current. For complex reasons, DC current transmission is hard to control, so the safety-conscious utilities transmitted it at low voltages. But by the time the DC current reached consumers, resistance had robbed it of 45 percent of its strength.

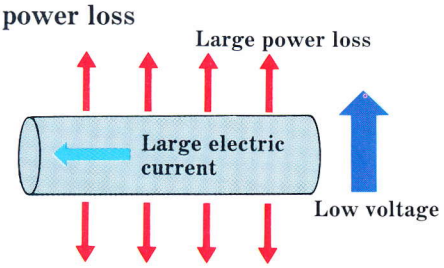
The solution was to transmit high-voltage AC current, which is easily converted by transformers (*below*). Because high-voltage transmissions require less current for the same amount of power, they sacrifice less energy to resistance. When AC current leaves the utility, step-up transformers boost it from 22,000 to 765,000 volts, and step-down transformers reduce it to the 110 or 220 volts used in homes.

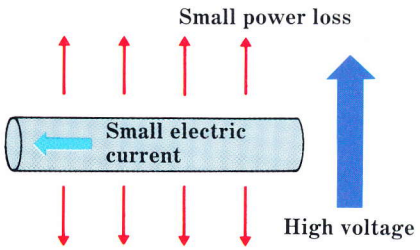
How transformers work

Transformers increase or decrease AC voltage. AC current enters a primary coil wrapped around an iron core. The current's back-and-forth motion sets up a changing magnetic field in the core. When the field moves from the core to the secondary coil, it generates AC current there. If the secondary coil has more loops than the primary, the output voltage will be larger than the input.



DC power loss

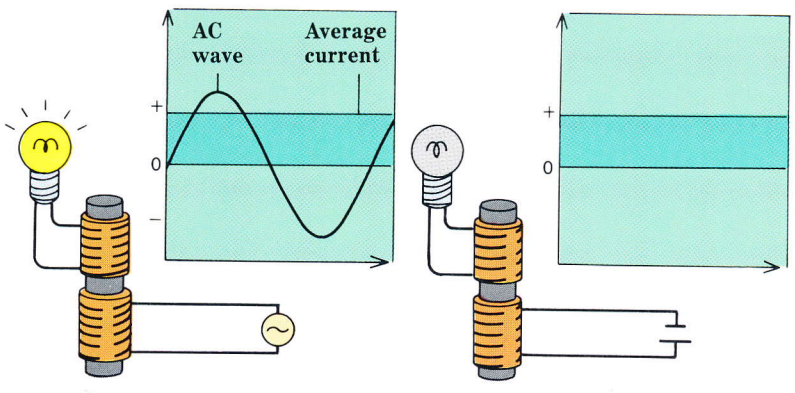




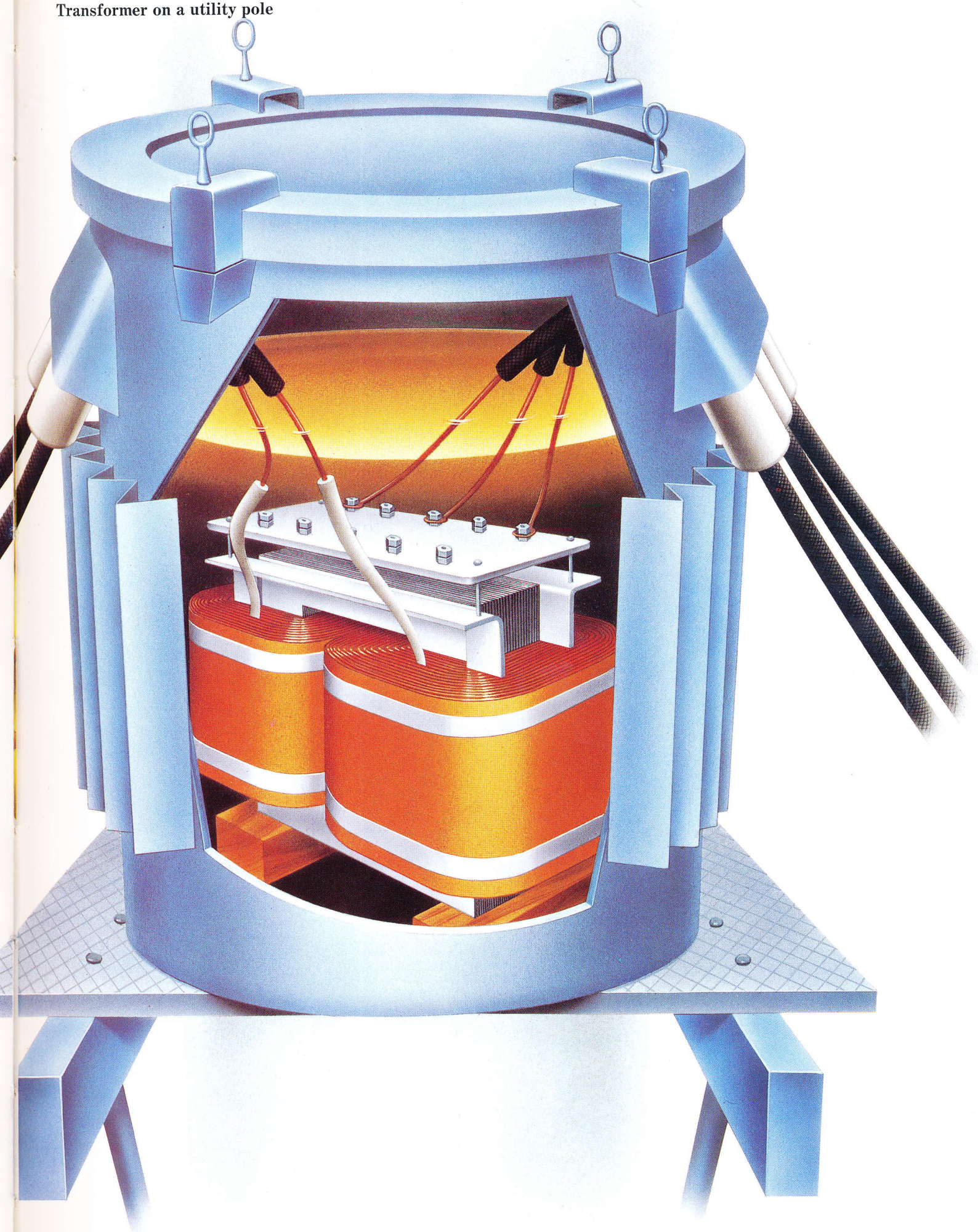
Electric power (P) is calculated by multiplying current (I) times voltage (V), or $P = I \times V$. As voltage increases, the current that is needed for a given power decreases. Lower-voltage DC power requires more current than high-voltage AC power to generate the same amount of electricity.

Changeable AC current

Unlike DC current, AC current switches direction. If AC current enters the primary coil of a transformer (*near right*), current fluctuations result in a changing magnetic field and a current in the secondary coil. DC current (*far right*) produces no fluctuations, and hence no current in the secondary coil.



Transformer on a utility pole



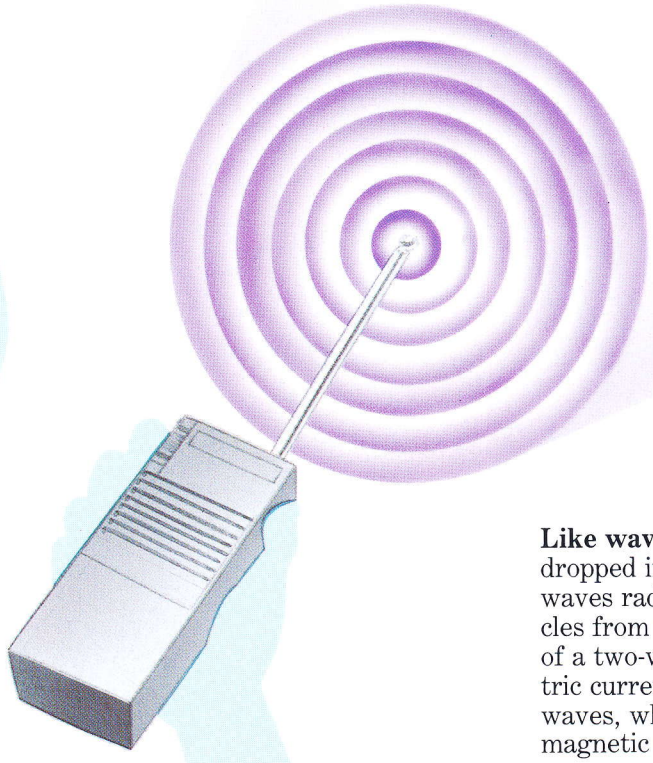
How do electromagnetic waves travel?

Any time an electric current varies its speed or course, it generates electromagnetic waves—fluctuations of electrical and magnetic force. One example is the changing current in a radio's transmitting antenna, which creates rings of expanding radio waves (*below*).

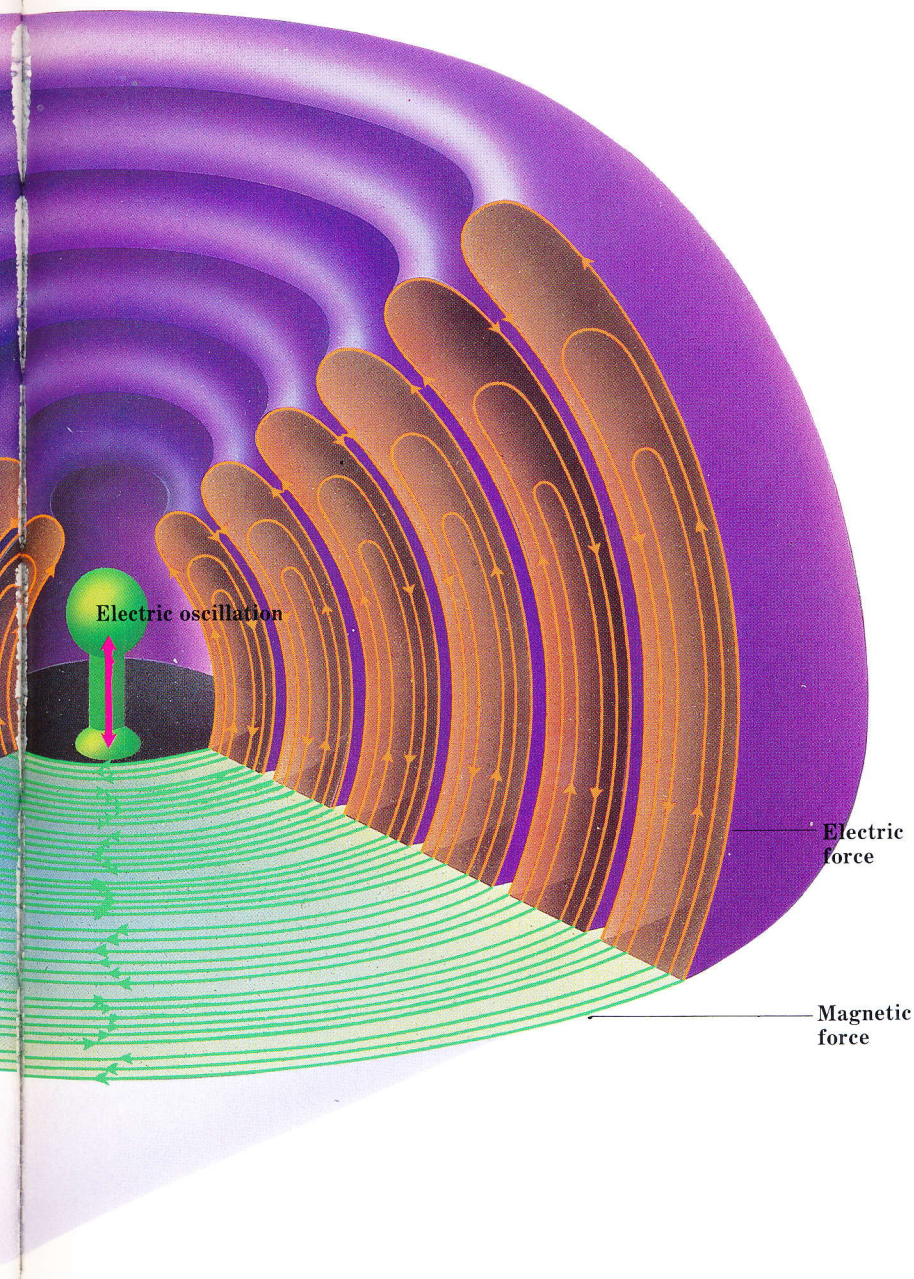
The energy of an electromagnetic wave is related to its wavelength—the distance from one wave crest to the next. The shorter the wavelength, the more energetic the wave. In order of decreasing wavelength, electromagnetic waves include radio waves, infrared rays, visible light, ultraviolet light, x-rays, and gamma rays. Gamma rays are a mere one-hundred billionth of a metre long, while radio waves can extend a few kilometres.

As electromagnetic waves spread outward at the speed of light, their electric and magnetic fields radiate at right angles to each other and to the direction of wave flow (*far right, top*).

Wave mechanics

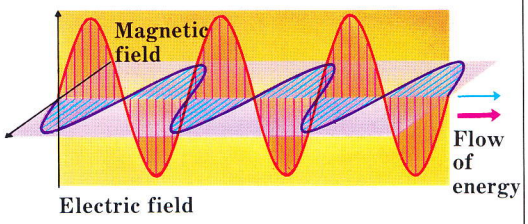


Like waves caused by a pebble dropped in a pond, electromagnetic waves radiate in ever-widening circles from the transmitting antenna of a two-way radio. Alternating electric current in the antenna produces waves, which consist of electric and magnetic fields.



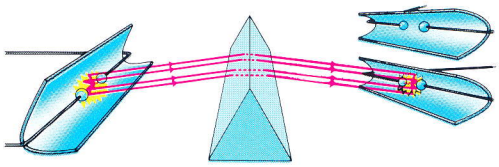
Charting electromagnetic waves

Electromagnetic waves travel in straight lines, with their electric and magnetic fields perpendicular to the energy flow.



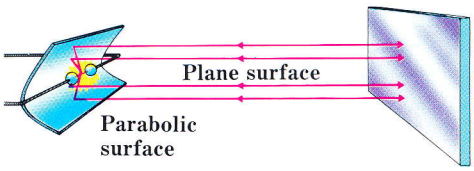
When waves refract

Like light, all electromagnetic waves slow down and bend when they enter substances at anything other than a right angle.

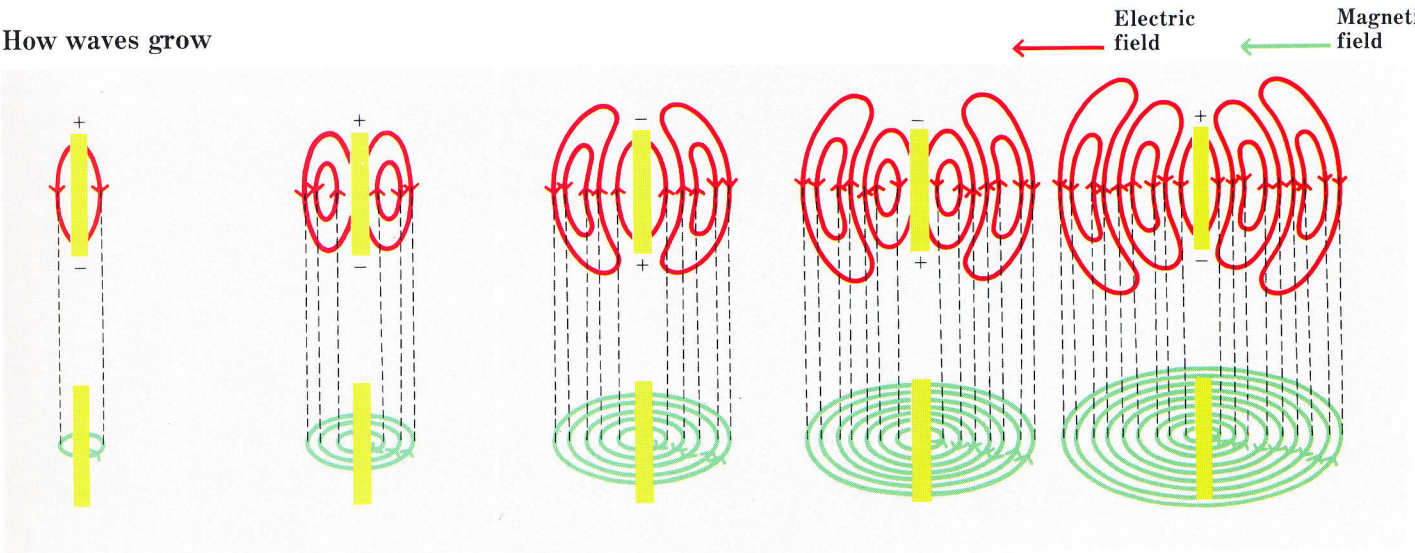


When waves reflect

If electromagnetic waves strike a metallic parabolic surface, they will focus at a single point.



How waves grow



The complex wave pattern that emanates from a transmitting antenna builds from a single fluctuation of current. When the current flows up the antenna, the electric field (*red*) moves from top to bottom and the magnetic field (*green*) rotates anticlockwise. As the current reverses direction, the electric and magnetic fields follow suit.

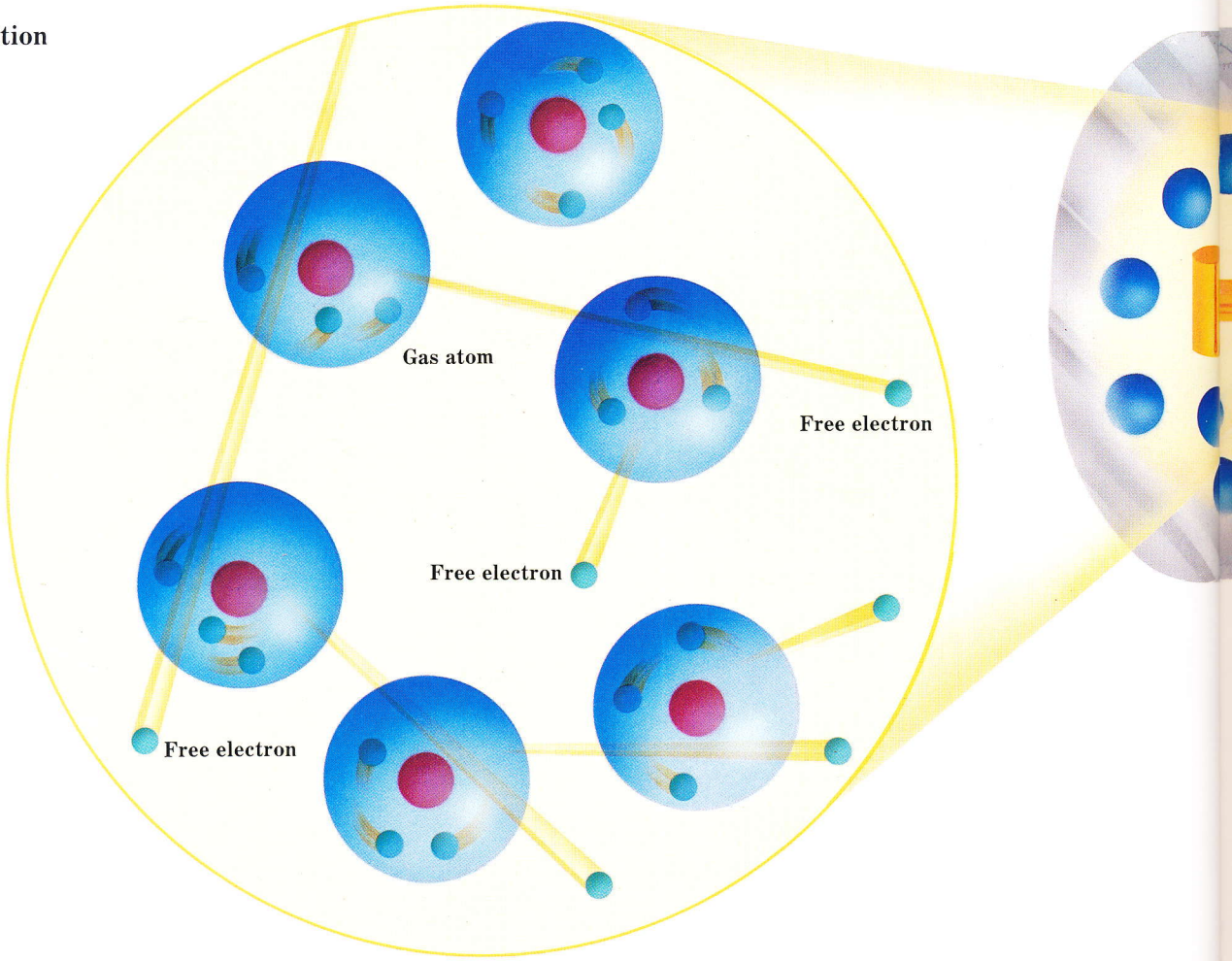
What other energy comes from atoms?

The current that powers machinery and generates electromagnetism is only one of the energy forms resulting from an atom's electrical properties. Another is radioactivity—the energy released when an atom's nucleus breaks down.

Atoms consist of negatively charged electrons, positively charged protons, and neutral particles called neutrons. Invisible forces of unimaginable strength bind an atom's protons and neutrons together in the nucleus. The nuclei of nearly all atoms disintegrate over time, unleashing some of this energy in the form of high-energy alpha and beta particles and gamma rays.

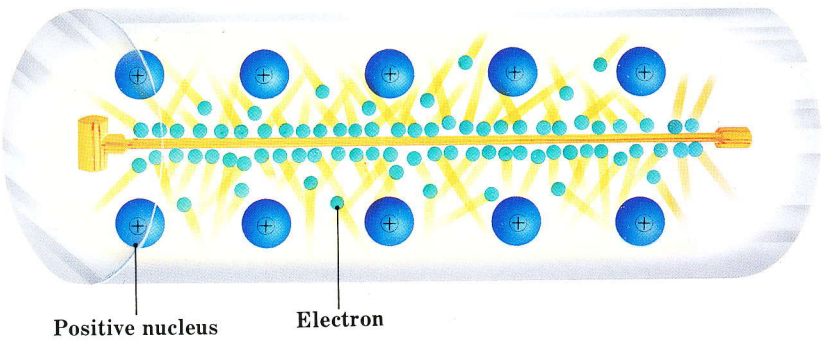
Though it cannot be seen, such radiation can be detected with electronic devices. The Geiger counter, perhaps the best-known radiation detector, translates the energy from radiation into measurable electronic signals.

Detecting radiation



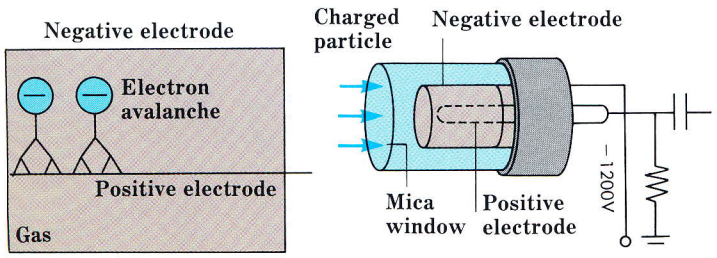
How a Geiger counter works

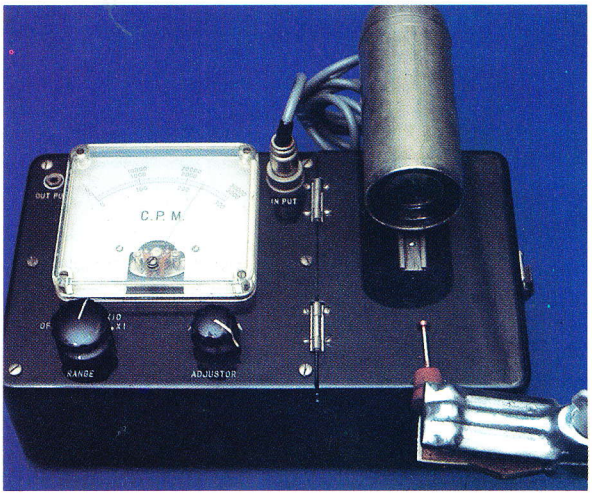
When a radioactive particle collides with a gas atom, it liberates an electron from the gas atom. This electron travels toward the centre electrode's positive voltage but may strike another atom en route. A succession of collisions sets off an electron avalanche that registers as an electric pulse on the centre electrode.



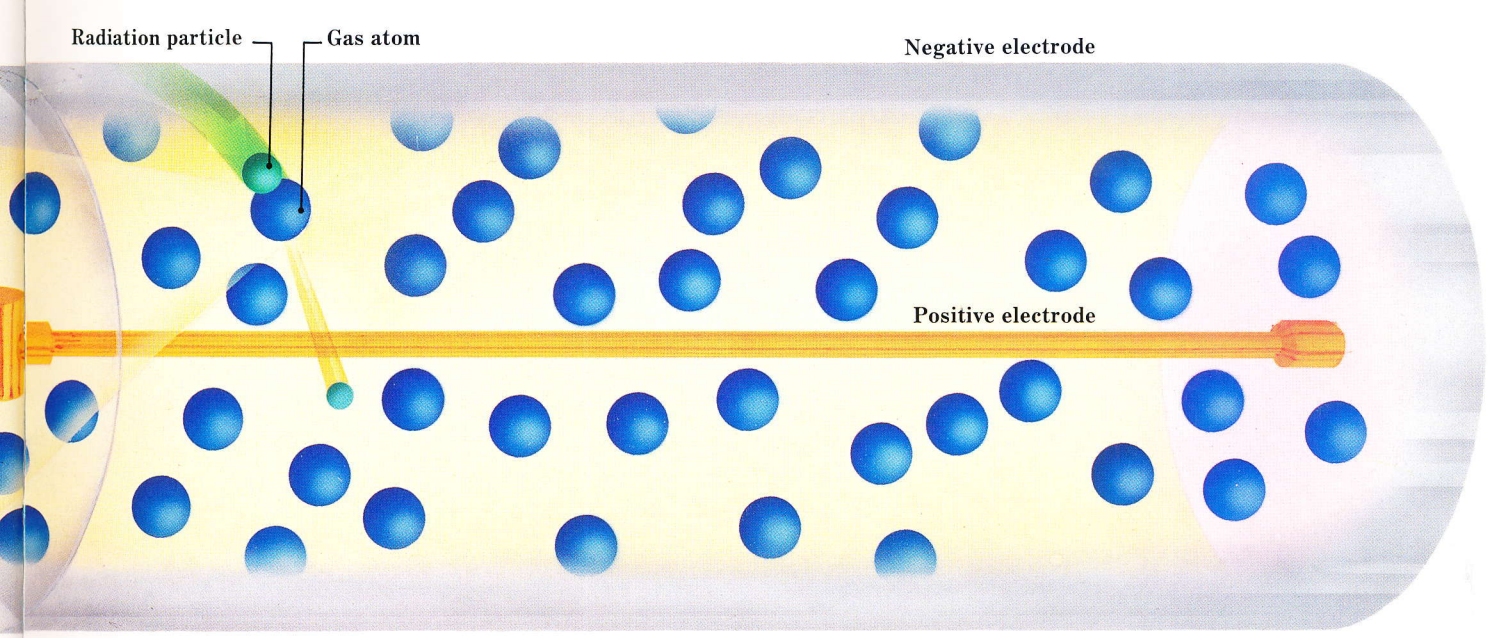
Geiger counter basics

The counter's metal tube doubles as a gas cylinder and negative electrode. In its centre is a positive electrode. Radiation enters the counter's mica window and bombards gas atoms, causing an electron storm between the electrodes.



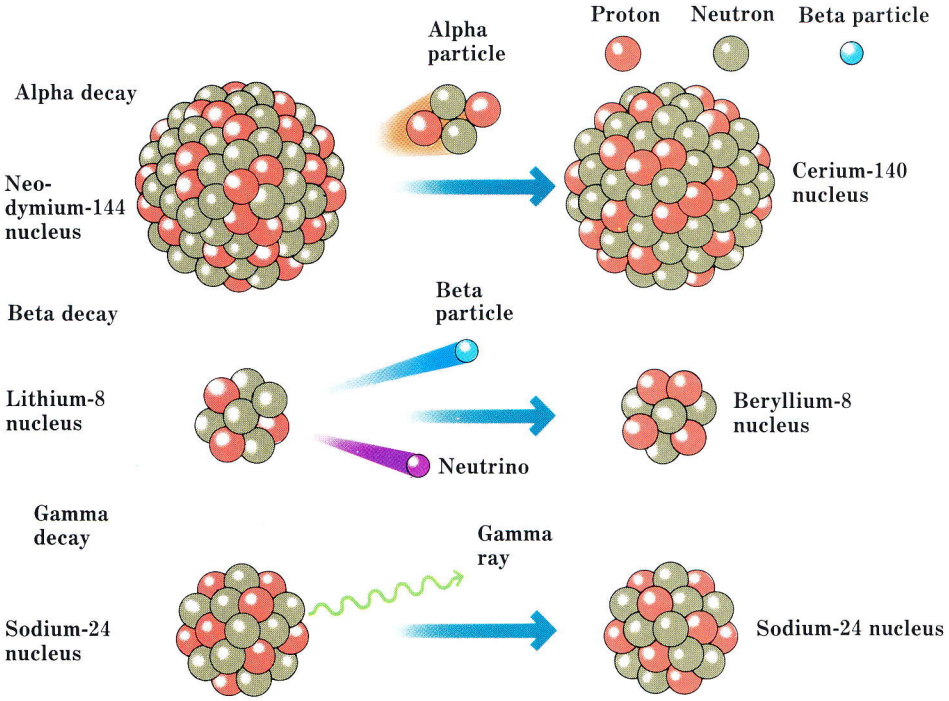


Geiger counter and pulse meter



Alpha, beta, and gamma decay

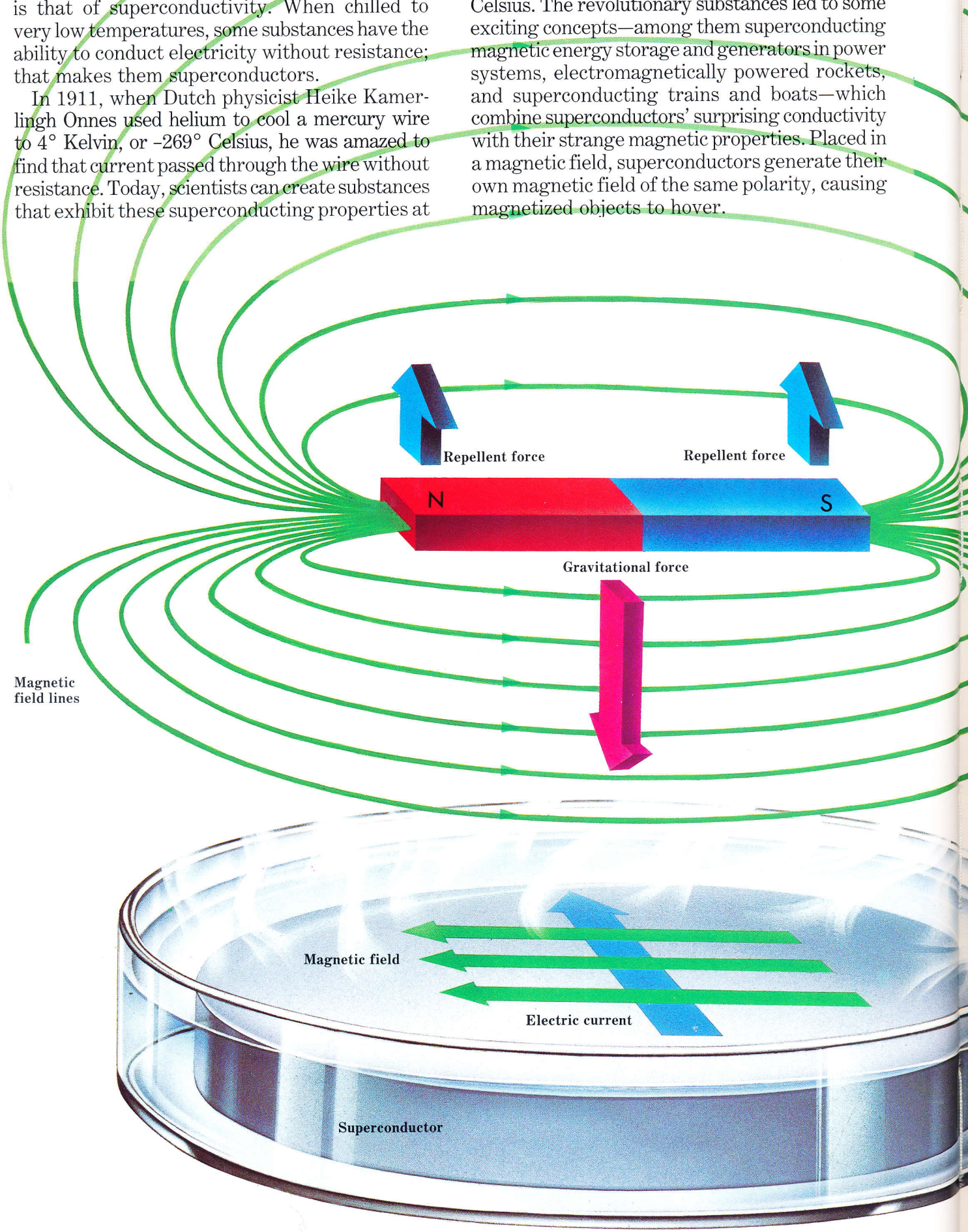
In alpha and beta decay, the elements become new substances. In gamma decay, only the arrangement of nuclear protons and neutrons changes. Shown here at top right, a neodymium-144 nucleus undergoes alpha decay, releasing an alpha particle to become a cerium-140 nucleus. At centre, beta decay turns lithium-8 into beryllium-8 by converting a lithium neutron into a proton and emitting a beta particle and a neutral particle known as a neutrino. In the bottom example of gamma decay, excess nuclear energy in a sodium-24 atom escapes as a gamma ray, but the atom is otherwise unchanged.

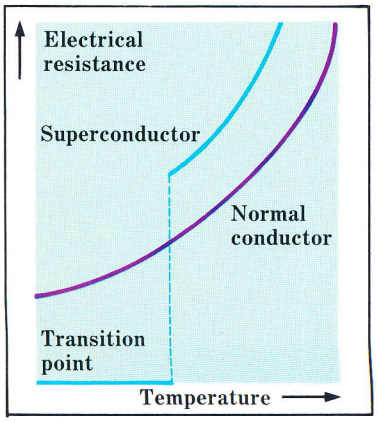


What is superconductivity?

Among this century's most exciting discoveries is that of superconductivity. When chilled to very low temperatures, some substances have the ability to conduct electricity without resistance; that makes them superconductors.

In 1911, when Dutch physicist Heike Kamerlingh Onnes used helium to cool a mercury wire to 4° Kelvin, or -269° Celsius, he was amazed to find that current passed through the wire without resistance. Today, scientists can create substances that exhibit these superconducting properties at higher temperatures, up to 100° Kelvin, or -173° Celsius. The revolutionary substances led to some exciting concepts—among them superconducting magnetic energy storage and generators in power systems, electromagnetically powered rockets, and superconducting trains and boats—which combine superconductors' surprising conductivity with their strange magnetic properties. Placed in a magnetic field, superconductors generate their own magnetic field of the same polarity, causing magnetized objects to hover.

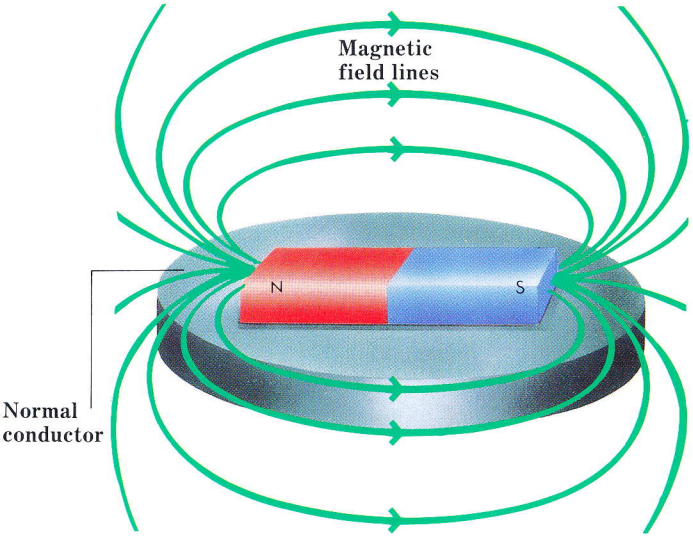




As the temperature is reduced, electrical resistance diminishes in normal conductors (*purple*), while superconductors (*blue*) reach a so-called transition point temperature at which their electrical resistance suddenly becomes zero.

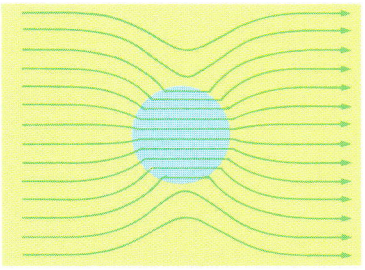
Conventional conductors

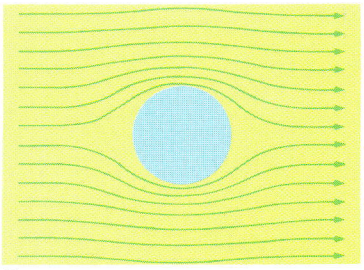
Not only do normal conductors channel current less efficiently than superconductors (*below*), but they also exhibit none of the superconductors' repellent properties, as shown in the illustration at far left.



The Meissner effect

A superconductor's magnetic properties are unlike those of a ferromagnetic conductor such as iron. Placed in a magnetic field, ferromagnetic materials become attracted to magnets. Superconductors, in what is called the Meissner effect, are repelled by magnets.


Ferromagnetic conductor

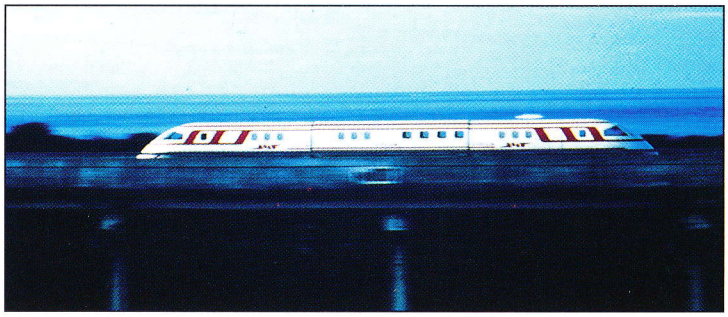

Superconductor

Superconducting levitation

A magnet placed above a helium-cooled superconductor induces an electric current and an electromagnetic field that repel the magnet's magnetic force, causing the magnet to float.

A superconducting train

One futuristic train design from Japan proposes superconducting magnets for propulsion. Superconductors in the train's undercarriage are repelled by the track's magnetic field, causing the train to levitate. Until the train is moving fast enough to lift off, it rolls on wheels.



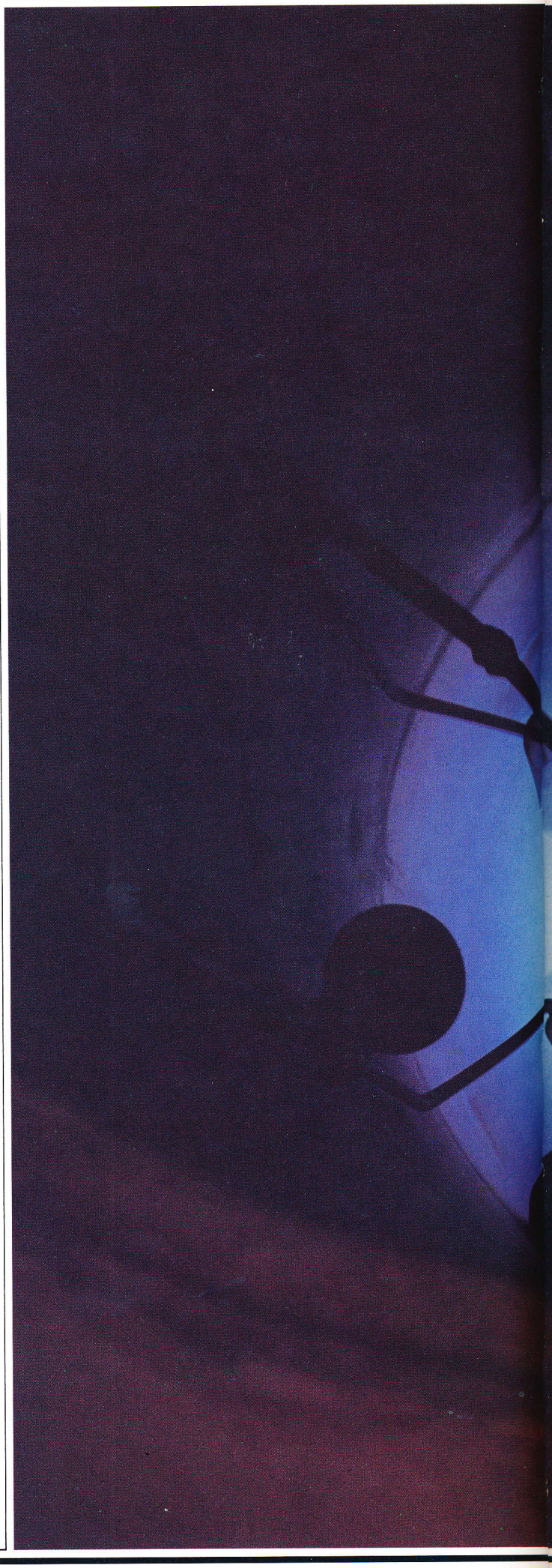
As the superconductors move faster and faster over the magnetic field in the track, the magnetic force increases, raising the train 10 centimetres above the track.

6

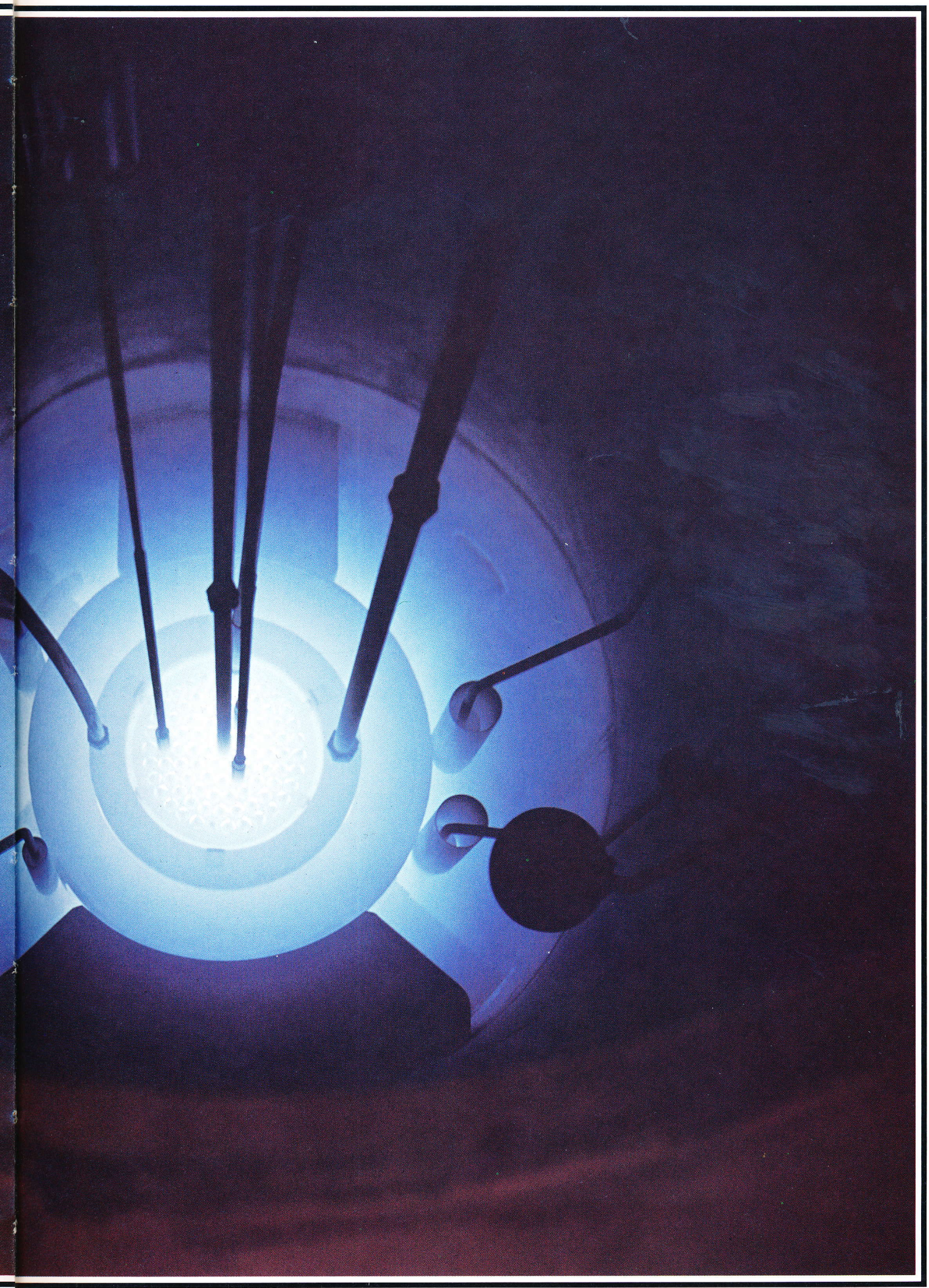
Generating electricity

In 1831, when English physicist Michael Faraday was conducting experiments with electricity, he hooked the two leads of a current-measuring device to a copper disc. He attached one electrode to the centre of the disc, the other to the edge, and spun the disc between the poles of a powerful magnet. As the disc twirled, electricity flowed through the circuit, and as the disc spun faster, the current increased. With this playful experimentation, Faraday, who became one of England's most famous scientists, had invented the dynamo, the first electrical generator.

Modern electrical generators, from portable petrol-powered models to huge hydroelectric generating stations, are more complex and produce far more current than Faraday's dynamo, but all of these generators operate on the same principle: When a magnet moves past a coil of wire, a current flows through the wire. This phenomenon is known as electromagnetic induction. Danish physicist Hans Christian Ørsted had discovered the connection between electrical and magnetic forces in 1819, when he observed that a moving electric current produces a magnetic field. Faraday, trying to understand this effect, created his hand-powered dynamo. Today, scientists harness the energy of moving water, sunlight, atoms, fossil fuels, hot underground rocks, and wind to move magnets past coils of wire, generating the electricity that makes modern society possible.

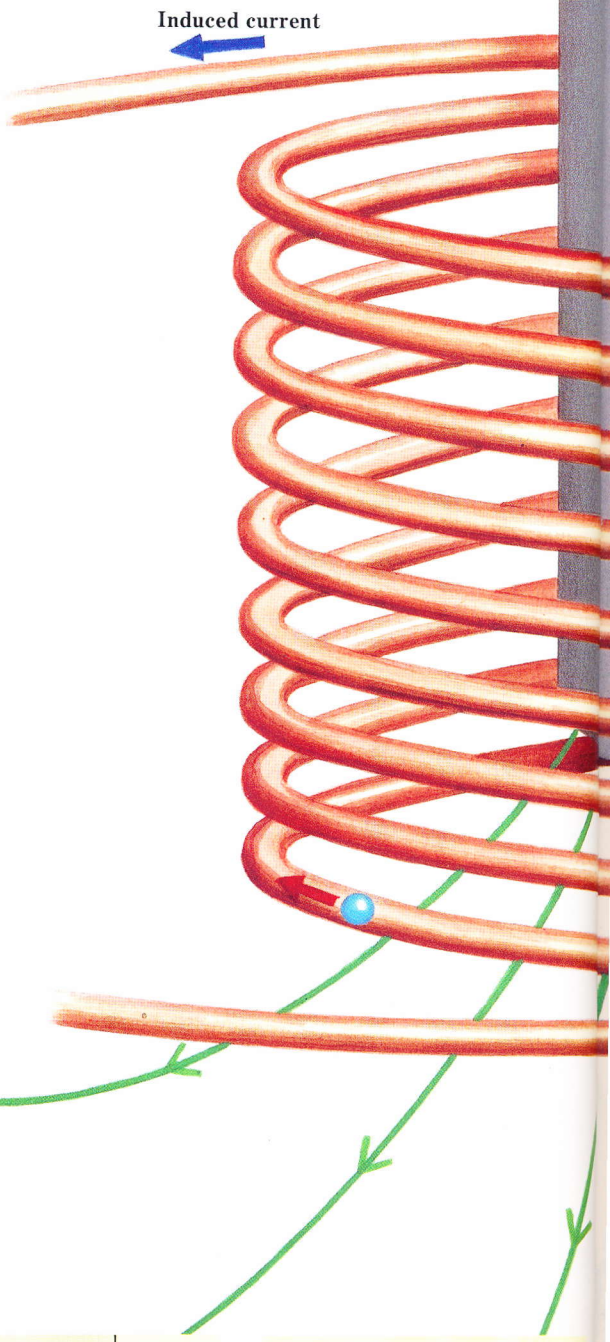


A faint blue glow emanates from the water covering a nuclear reactor core, the heart of a nuclear-powered generator. The splitting of atoms is just one of many ways in which power is produced to run electric generators.



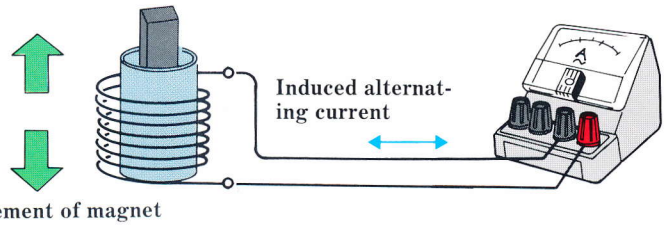
How does an AC generator work?

A generator converts mechanical energy into electrical energy by means of a wire coil that is rotated in a magnetic field. An electric current is also produced when the force lines of a magnet pass through a wire coil (*right*). The electrons (*blue*) flow toward the magnet's positive pole, and the current moves from the positive pole to the negative pole. As long as the magnetic field moves through the coil, or conductor, current is induced in the conductor. The same principle applies when a wire coil passes near a magnet (*far right*) and the coil moves through the magnetic field. The induced current flows in such a way that it repels the magnet when the magnet comes close to the coil, and it attracts the magnet when the magnet moves away. Each time the magnet changes direction relative to the coil, the current changes direction, or alternates, as well. As long as a device mechanically rotates the conductor, or the magnetic field, the generator will continue to produce a flow of alternating current (AC).



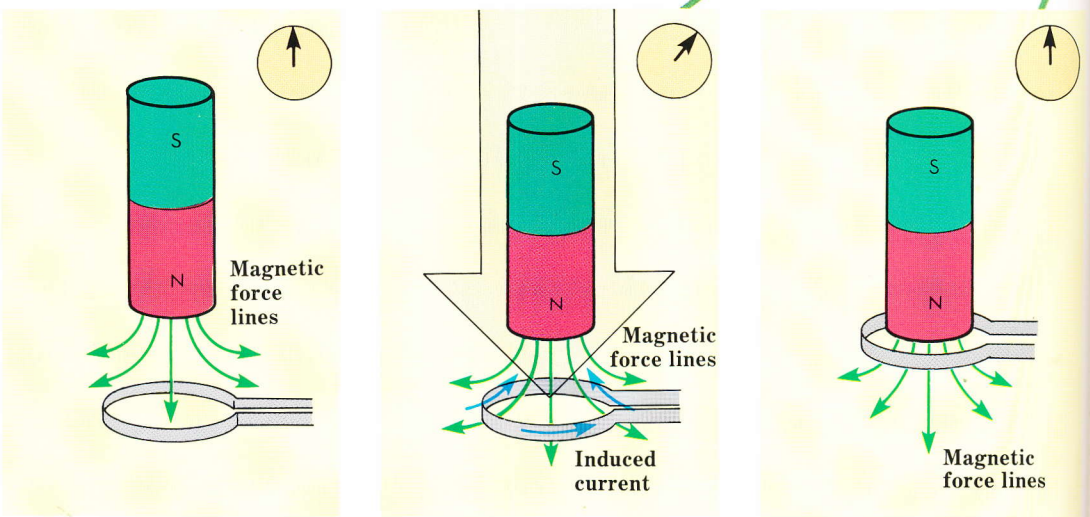
Changing current direction

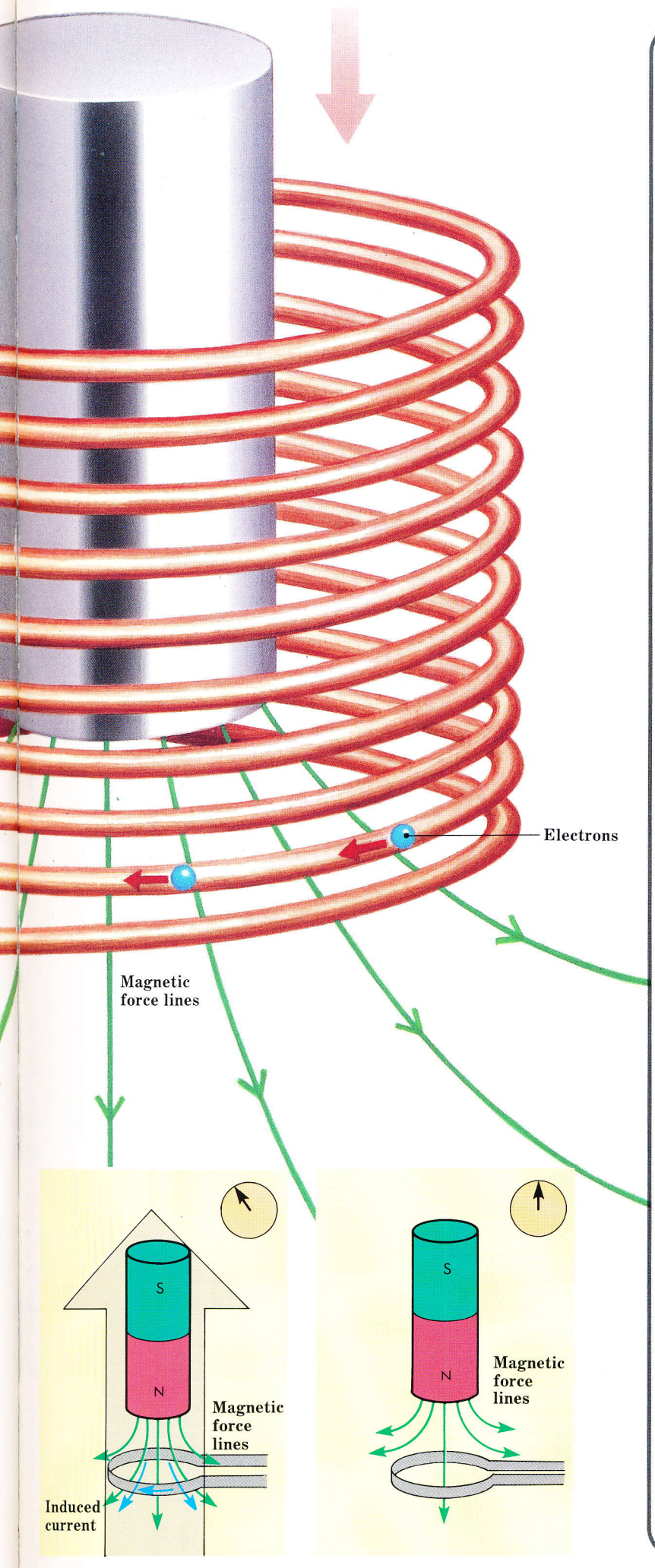
When a magnet is moved through a wire coil (*below*), it induces an electric current to flow in the coil. This current causes the needle on the ammeter (*pages 76-77*) to swing away from the zero position. When the magnet is pulled back through the coil, the current changes direction, or alternates, and the ammeter needle swings to the opposite side of the zero position.



Alternating current

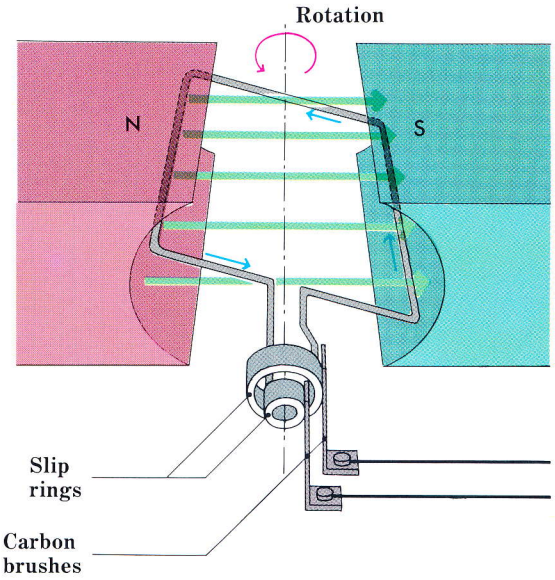
A magnet will not induce a current until its force lines cross the wire coil. Moving a magnet's pole into a coil induces a current to flow in the wire loop. When the magnet stops moving, the current (*blue arrows*) stops flowing (*middle diagram*). Pulling the magnet away from the coil induces a current flowing in the opposite direction.





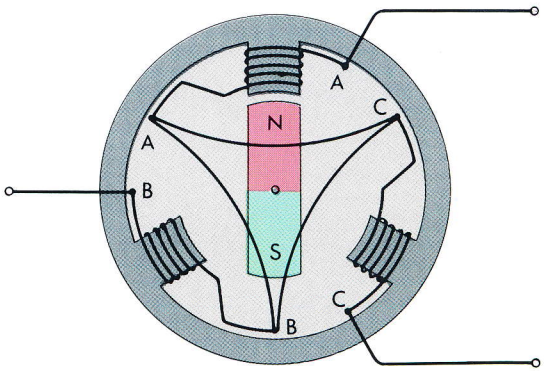
A basic AC generator

In a simple AC generator, a wire loop spins between the poles of a stationary magnet. Each end of the loop connects to a slip ring that rubs against a conducting carbon brush (*below*). The induced current flows to the inner slip ring as its half of the loop passes the north pole, but the current flows toward the outer ring as the other half of the loop spins past the north pole.

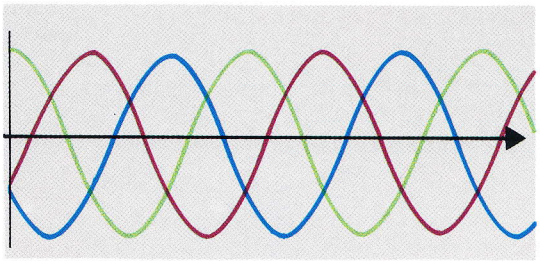


Three-phase AC generator

An economical way of producing strong alternating current is to use one magnet spinning past several coils. In the common three-phase generator (*below*), three coils sit equally spaced around the magnet. Each coil produces an alternating current as the magnet passes (*bottom*).



Three-phase AC generator



Outputs from three coils

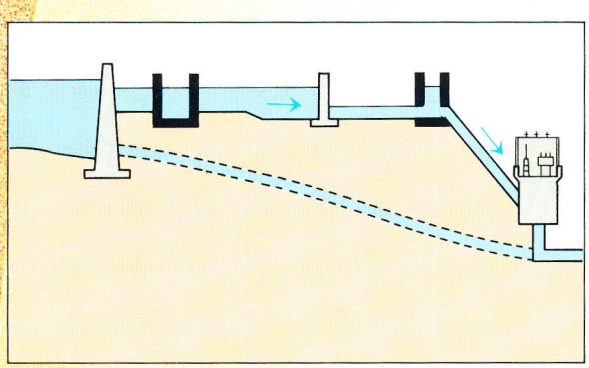
How does water provide electricity?

Water has long provided power to meet human needs, and today, hydroelectric generators produce about 20 percent of the world's electricity. Water from behind a dam falls past giant turbine blades, spinning them at speeds of 125 to 750 revolutions per minute. The whirling blades provide the mechanical power that turns the huge magnet inside an AC generator. How much power is produced depends on the water's "head"—how far the water falls before reaching the turbine. Engineers have developed turbines to harness the power from a head as low as six metres and as high as 1,770 metres.

Sluice tower

Dam

Hydroelectric power generation



A hydroelectric plant must have a dam (*above, left*) to hold back water from the river and a conduit to carry that water to the power plant (*right*).

Water conduit

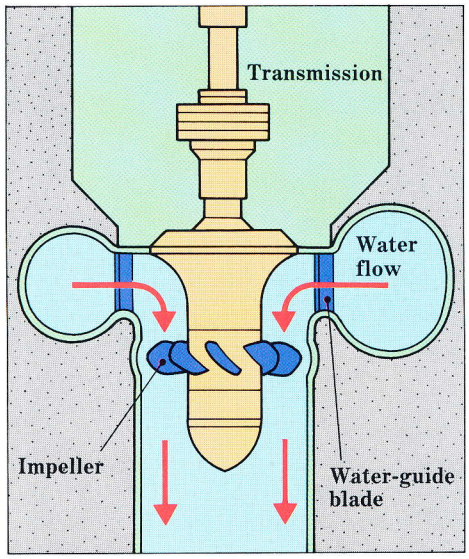
Water drains out

Water flow

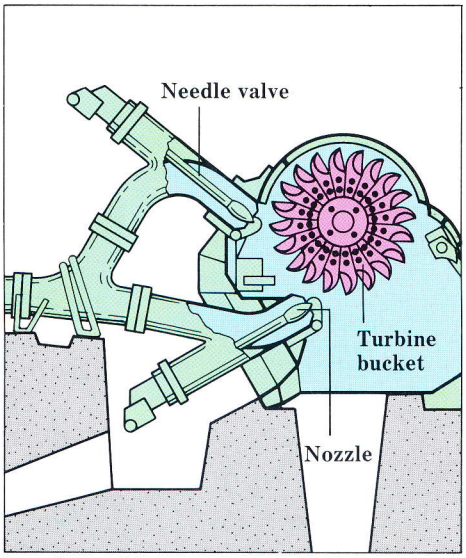
Two hydroelectric turbines

Low-pressure water turns the impeller below to drive a propeller turbine.

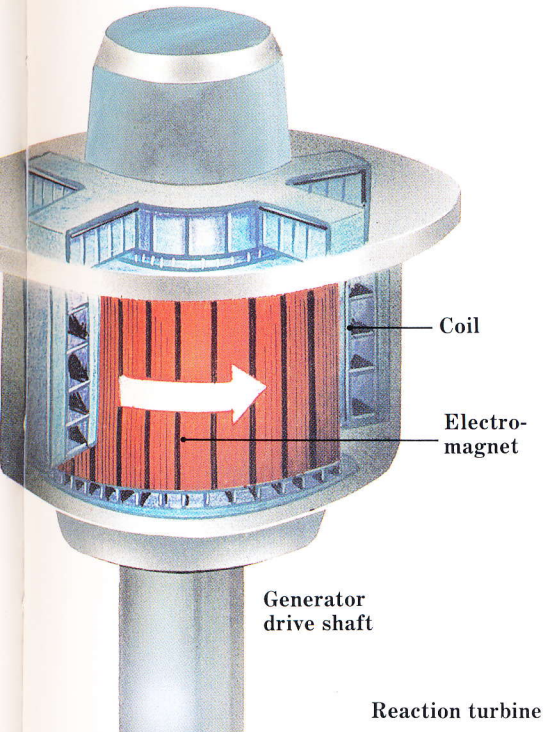
An impulse turbine sprays water at high pressure onto spinning buckets.



Propeller turbine



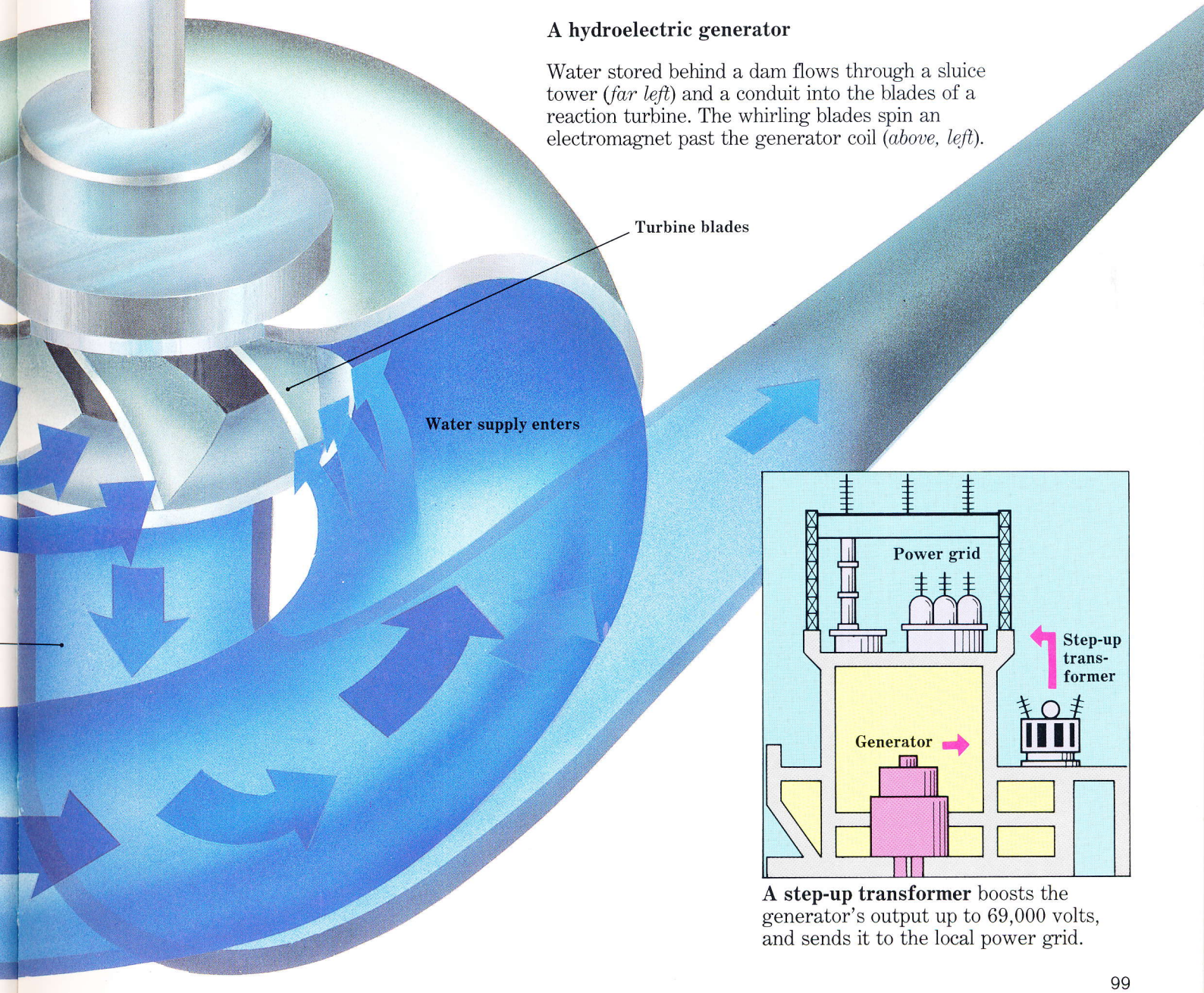
Impulse turbine



Reaction turbine

A hydroelectric generator

Water stored behind a dam flows through a sluice tower (*far left*) and a conduit into the blades of a reaction turbine. The whirling blades spin an electromagnet past the generator coil (*above, left*).



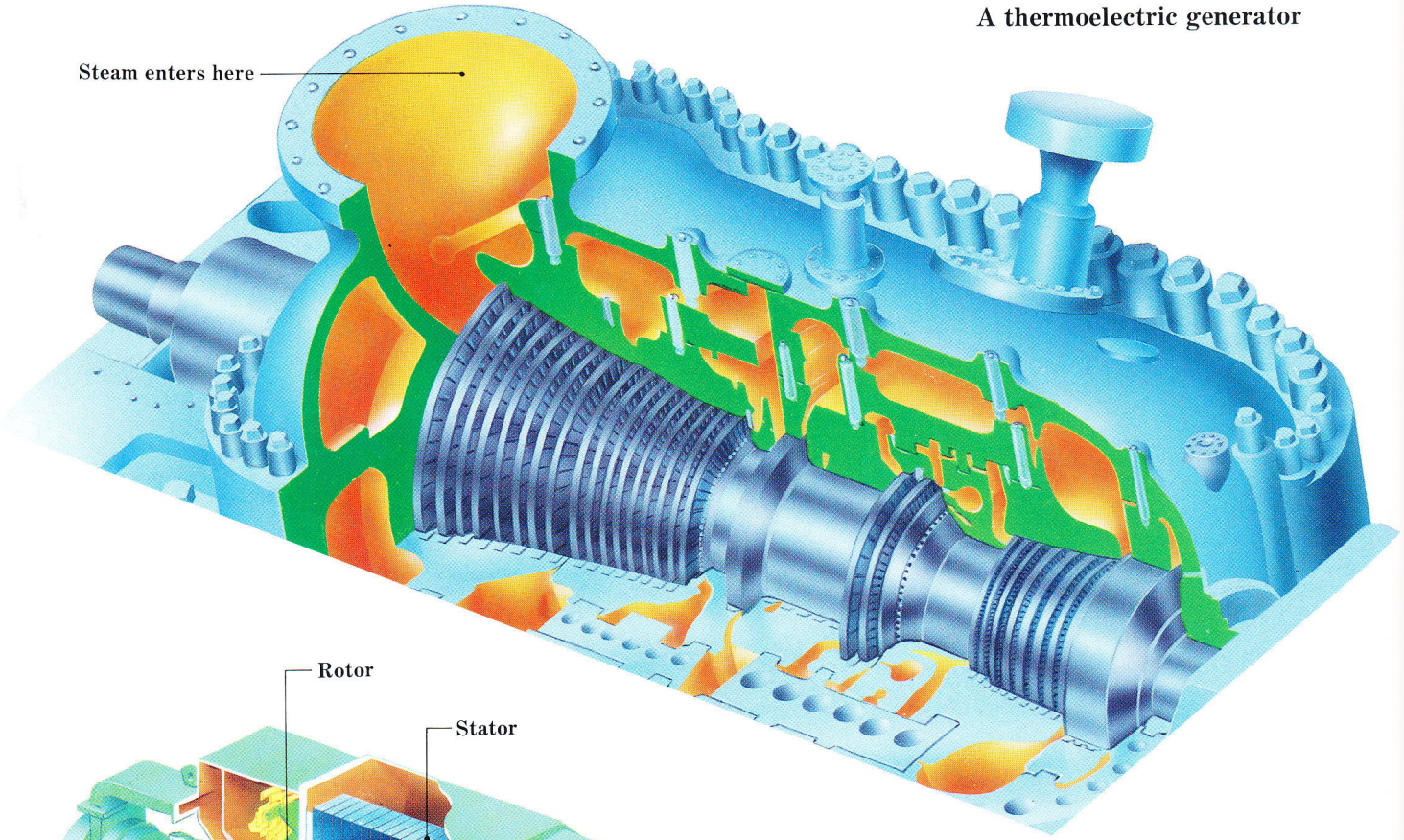
A step-up transformer boosts the generator's output up to 69,000 volts, and sends it to the local power grid.

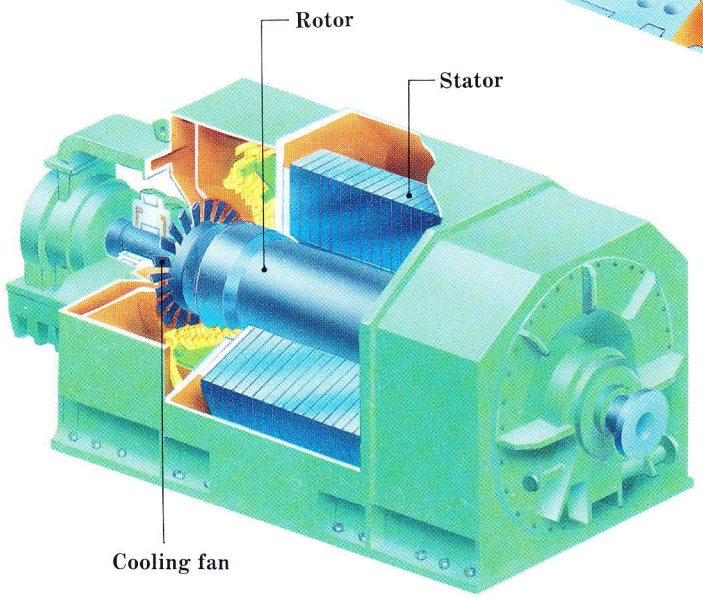
How do power plants use fossil fuels?

A thermoelectric power plant uses energy released from the burning of fossil fuels—coal, oil, and natural gas—to convert water into high-pressure steam. The steam, at a pressure of about 24 million newtons per square metre and a temperature of 524° Celsius, drives a turbine. The turbine spins a huge magnet inside a generator, producing electricity.

Modern thermoelectric plants capture about 40 percent of the energy released from burning fuels and convert it into electricity; the rest of the energy is lost as heat. Many power plants in Europe use the waste heat to warm nearby homes and businesses. Producing both usable heat and electricity increases the energy efficiency to 80 percent.

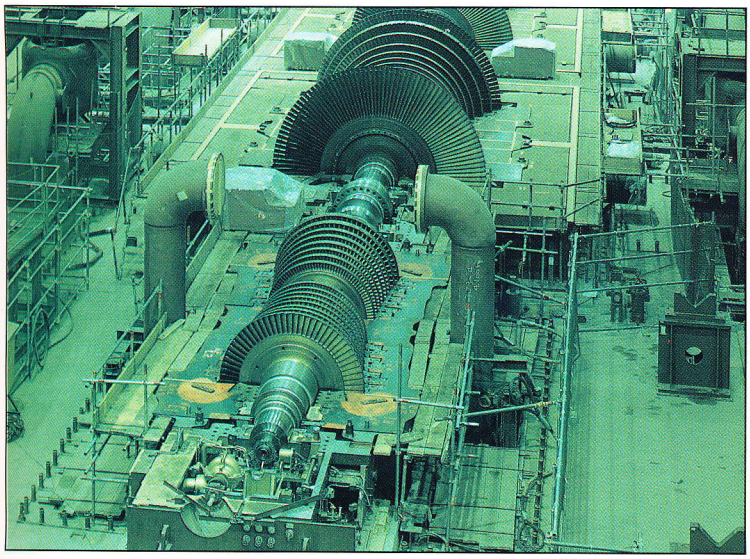
A thermoelectric generator





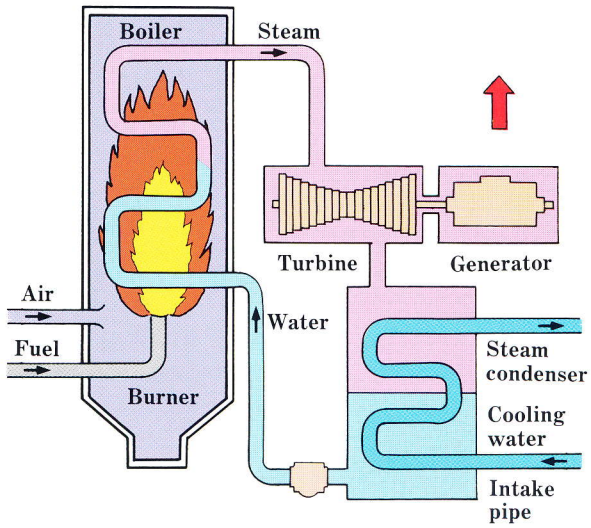
A cutaway view

The typical generator (*left*) in a thermoelectric plant is driven directly by the steam turbine, which turns at 3,000 revolutions per minute. In such generators, the magnets—also called rotors—spin while the coils, or stators, are stationary. A cooling system prevents overheating.



Impeller blades are visible in this steam turbine.

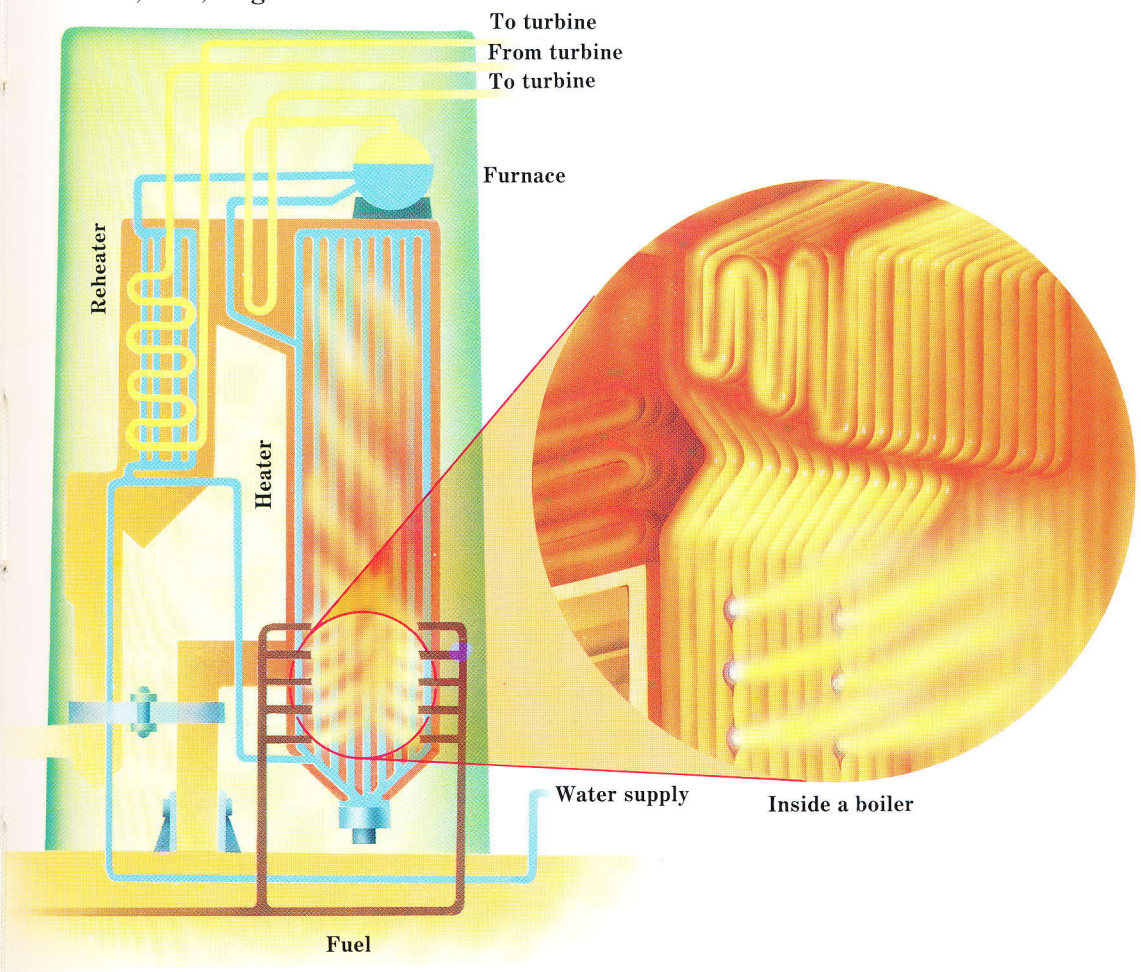
A typical steam turbine (*left*) contains two sets of blades. High-pressure steam, fresh from the boiler, enters the turbine chamber and spins the first set of blades. The steam is reheated and circulated back to the turbine chamber to drive a second set of blades that operate at lower steam pressure.



Generating power with steam

In a thermoelectric plant, fuel burns in a boiler, producing an intensely hot flame. Pipes carry water through the flame, and the heat turns the water to high-pressure steam. The steam drives a turbine, providing the mechanical energy that a generator converts to electricity. After leaving the turbine, the steam travels to a condenser, where it circulates over pipes carrying cold water and is turned back into water.

An oil, coal, or gas boiler



Inside a boiler

A boiler is filled with water-carrying pipes folded upon themselves many times over. This configuration maximizes the amount of heat transferred to the water and thus produces the most steam.

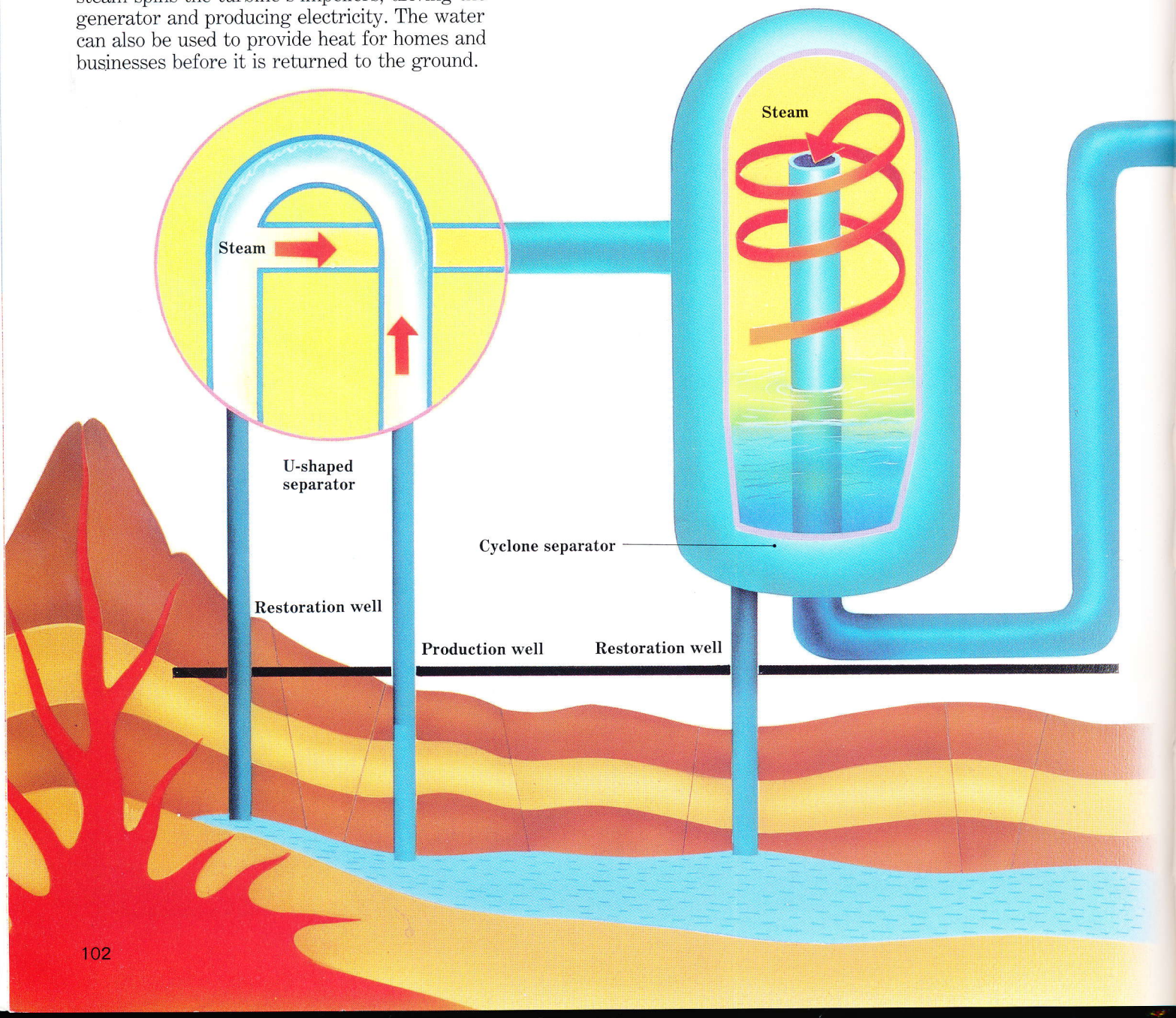
What is geothermal generation?

Fifteen kilometres beneath Earth's surface, an almost limitless source of energy waits to be exploited. It is not oil, coal, or natural gas, but the energy from the rocky, hot interior of 420° Celsius or more. This intense heat, known as geothermal energy, turns underground water into the steam that erupts from geysers such as those in the Tiwi steam fields in the Philippines' Albay province. It also powers steam-turbine electrical generators built over geysers in California, New Zealand, and Italy. These natural pockets of steam, within two kilometres of the surface, are too rare to provide large amounts of natural geothermal energy worldwide. But holes drilled 15 kilometres deep into the ground can reach geothermal energy and create steam anywhere a power plant is needed.

There are two ways to drill for geothermal energy, both using holes bored 15,000 metres deep or more. One method uses a single hole about half a metre in diameter. Cold water poured down the hole is heated by the surrounding rocks and returns as steam through an insulated inner pipe. The other method uses several narrower holes. Water pumped down one hole percolates through the hot rocks and returns to the surface as steam through insulated pipes in "riser" holes.

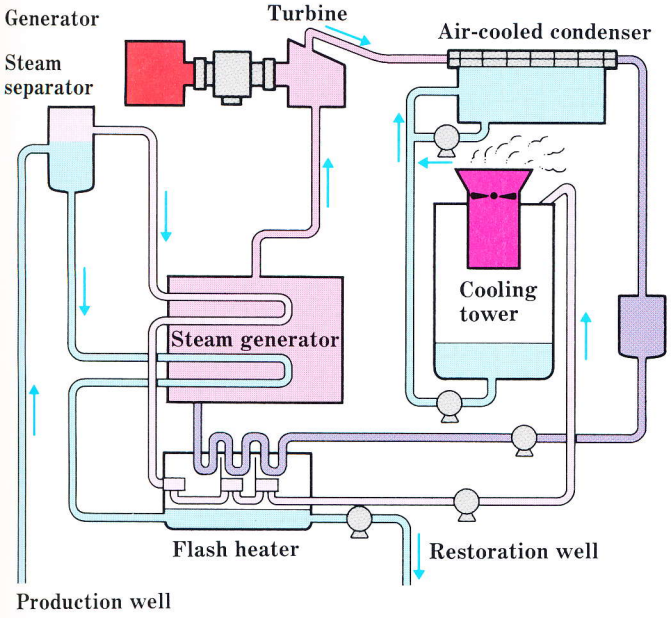
Getting steam from Earth

Water pumped into a geothermal well returns to the surface as high-pressure steam and superheated water (*below*). This mixture passes into a cyclone separator, a device that traps the water and lets the steam flow to the turbine. The steam spins the turbine's impellers, driving the generator and producing electricity. The water can also be used to provide heat for homes and businesses before it is returned to the ground.



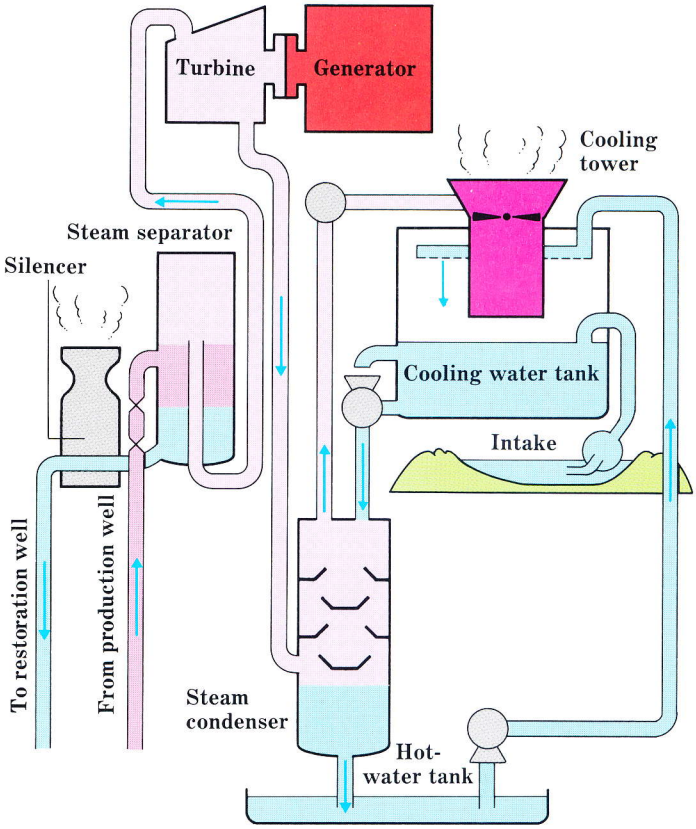
Two-way generation

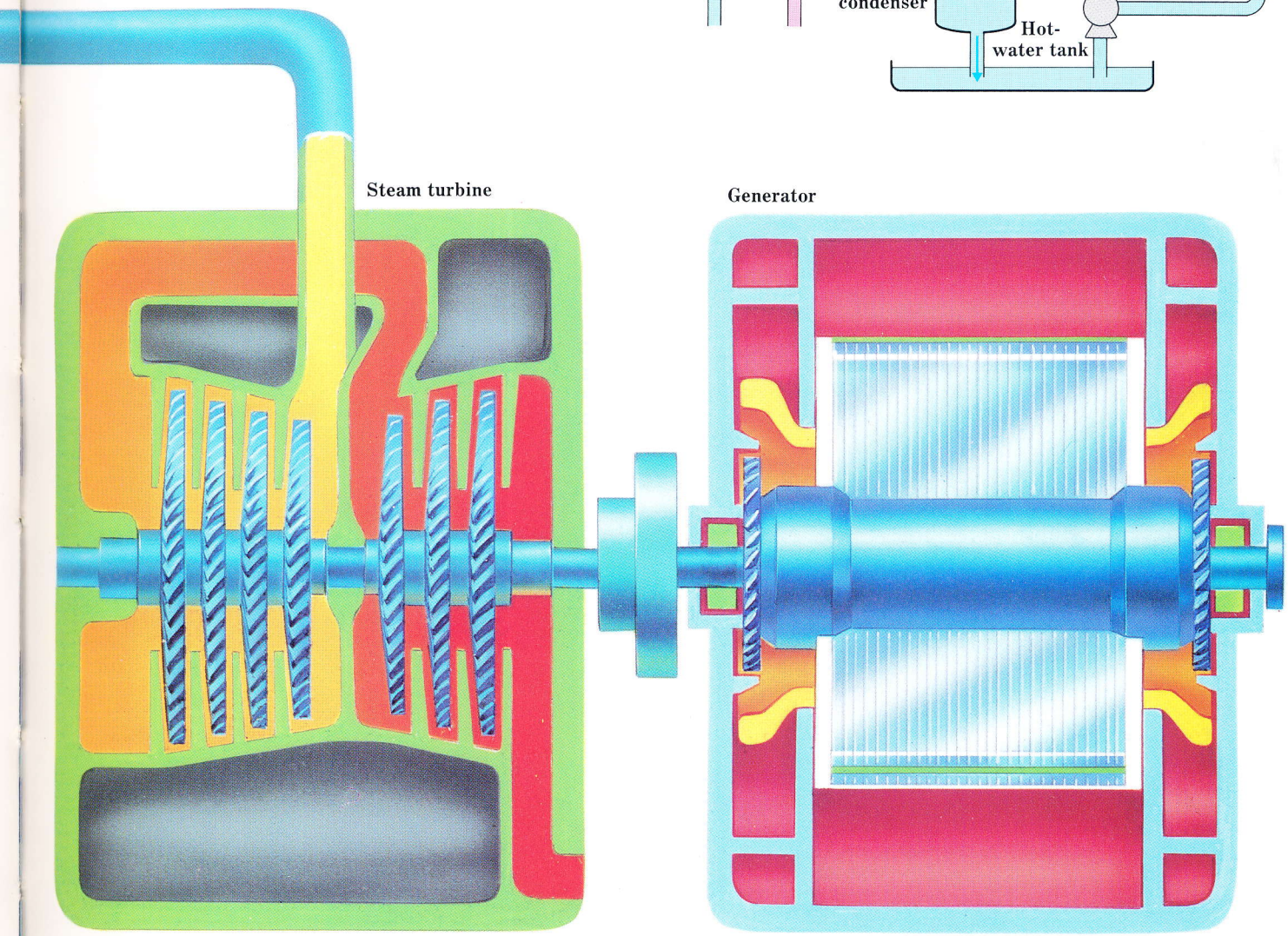
A plant like this produces electricity with hot geothermal water to vaporize a chemical compound (*purple*) that has a boiling point far below that of water. The pressure of the chemical steam drives a turbine.



The steam-water cycle

This plant uses steam (*lilac*) that is separated from the hot water (*pink*) at the production well, then used to drive the turbine. The water is restored to the ground. The steam is later cooled and recirculated as water.

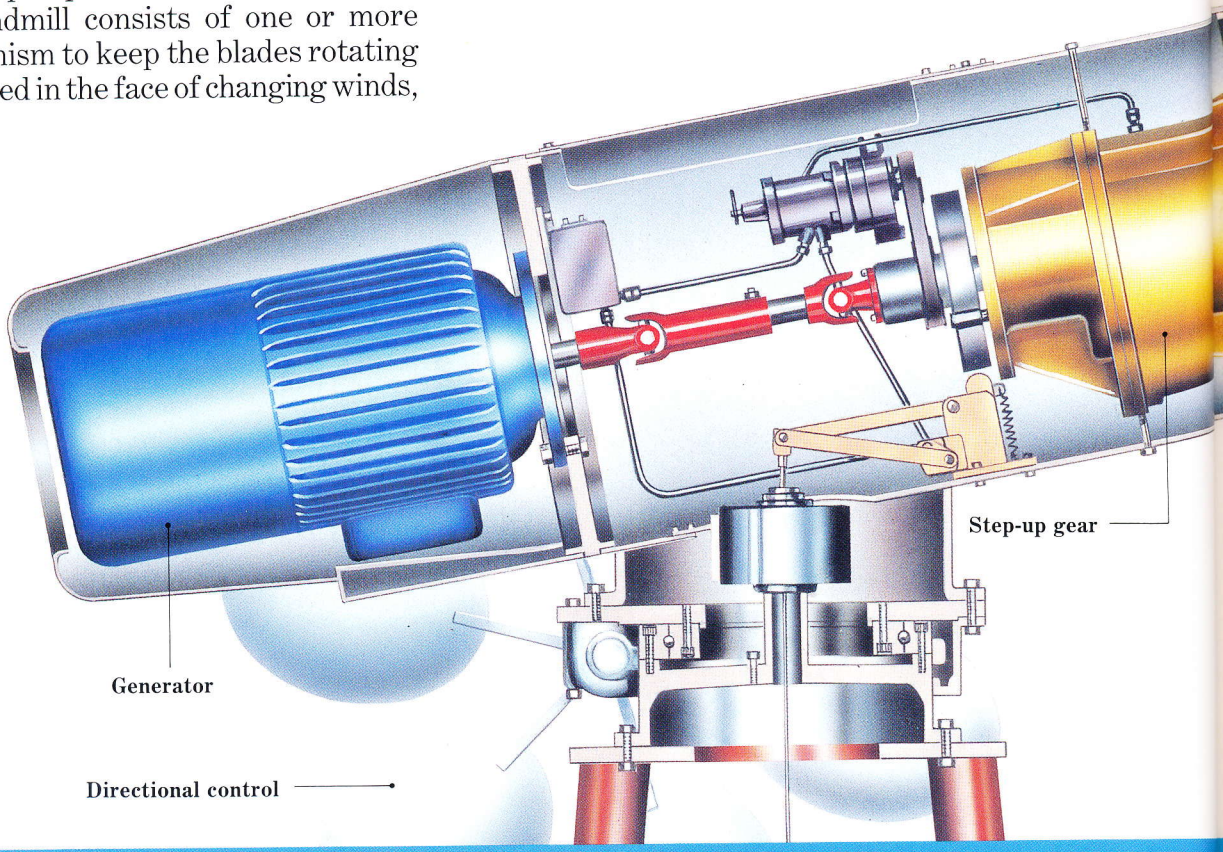


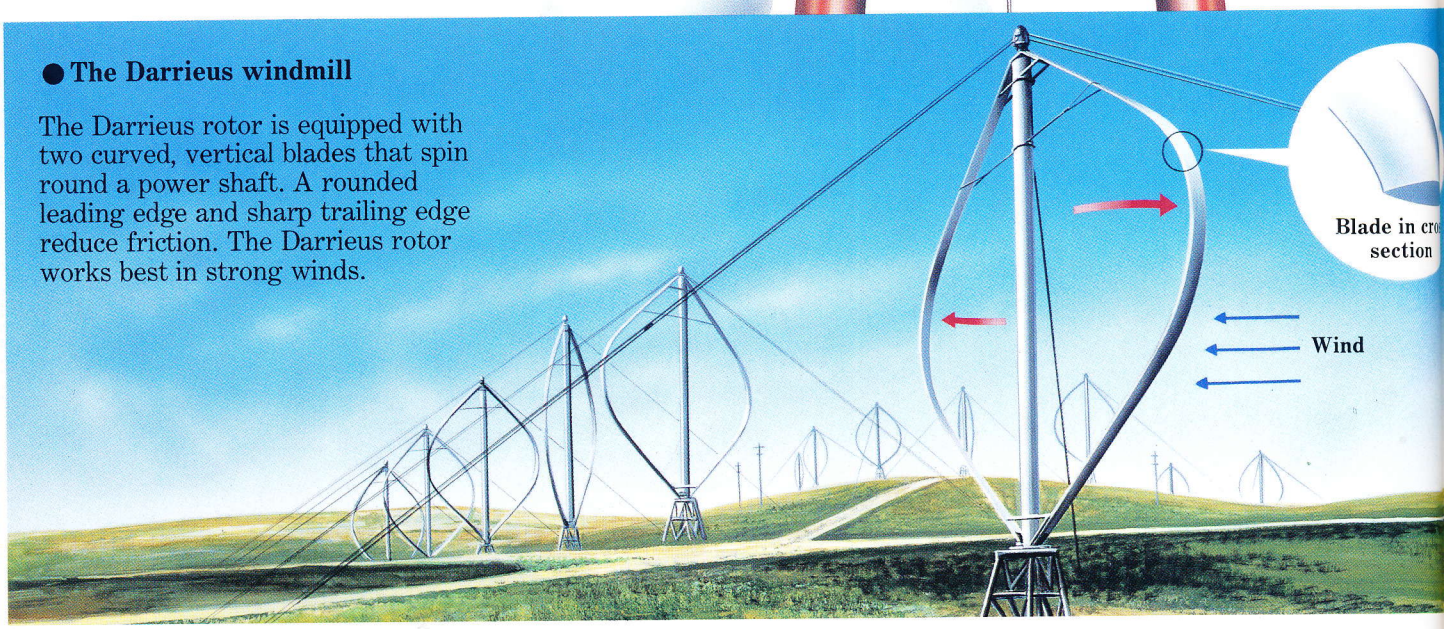


How is wind used as a power source?

In many parts of the world, including California and the midwestern United States, brisk winds are common enough to serve as an inexpensive and reliable source of nonpolluting energy for generating electricity. Windmills come in a variety of shapes and sizes, each designed for a particular task and setting. For example, the Darrieus windmill, which has a rotor that resembles an eggbeater, works most efficiently at high wind speeds. The kind of windmill with four or even eight blades that is used on a farm is best suited for generating small amounts of direct current to run water pumps in areas with mild winds.

The basic windmill consists of one or more blades, a mechanism to keep the blades rotating at a constant speed in the face of changing winds, and a generator. A widely used kind of windmill (*below*) has two blades and looks like an aeroplane propeller mounted on a tall pole. But unlike an aeroplane propeller, these windmill blades are able to change shape in response to varying winds. They are built this way because windmills that are part of an electrical grid need to operate at near-constant speeds to keep their electrical output steady. Gears and wind brakes also help to keep the windmill operating at peak efficiency.

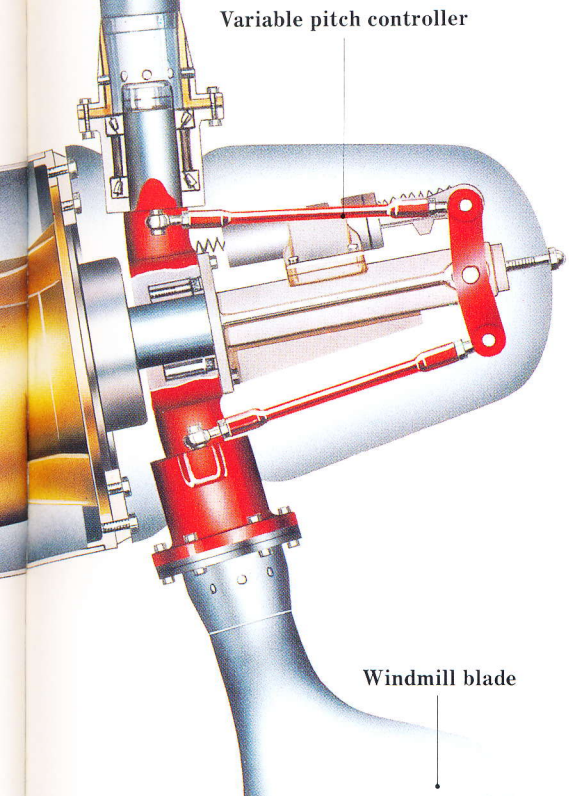




● The Darrieus windmill

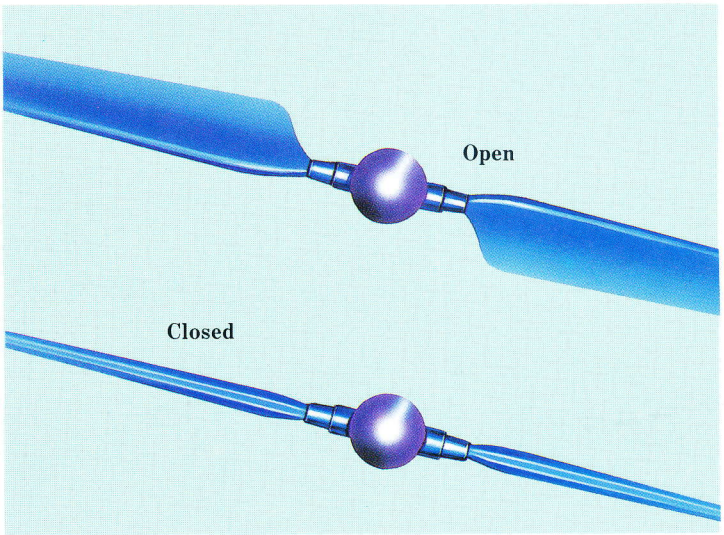
The Darrieus rotor is equipped with two curved, vertical blades that spin round a power shaft. A rounded leading edge and sharp trailing edge reduce friction. The Darrieus rotor works best in strong winds.

This wind farm in northern California in the United States has dozens of windmills that convert the area's strong winds into electricity. Each windmill is carefully placed so that it will not prevent the full force of the wind from reaching any of the others.

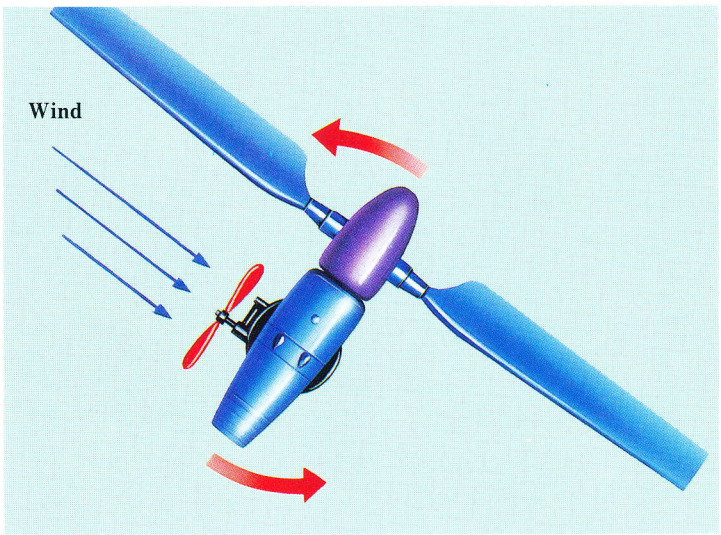


Windmill blade

Adjusting to changing winds



In weak winds, the windmill blades above open automatically (*top*) to catch the maximum wind energy. When wind increases, the blades close (*bottom*), so as not to turn too fast.



A small propeller on a directional control windmill keeps the main propeller facing into the wind. This helps the windmill to capture the wind's energy most efficiently.

How is the ocean's power harnessed?

The ocean can be tapped for three different forms of energy—tidal, wave, and thermal power. All are proven, but none is yet operating commercially. To capture the energy in tides, a dyke is built across an estuary (*below*). Tunnels running through the dyke house turbines and generators. When the tide comes in, the water level is higher on the ocean side. This imbalance forces water to flow through the tunnel to the low water side, spinning the turbine as it goes. At low tide, the water is higher in the estuary than on the ocean side. The water flows back through the tunnel, producing more electricity.

Wave power also uses the ebb and flow of water to spin a turbine inside a bottomless float. When a wave swells beneath the float, it forces air past the turbine blades twice—when the water is high and when it drops.

Ocean thermal power generation uses the sharp difference in temperature between the ocean's surface and its depths to evaporate and condense a liquid that will vaporize at a low temperature. The vapour drives a turbine.

Tidal power generating station

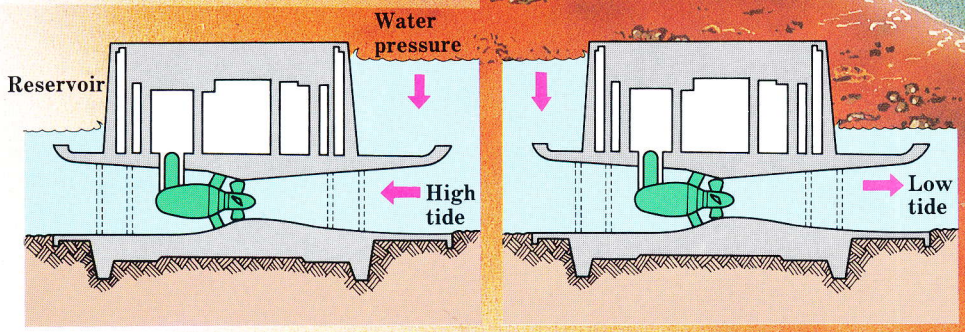
Dyke

Generator

Turbine propeller

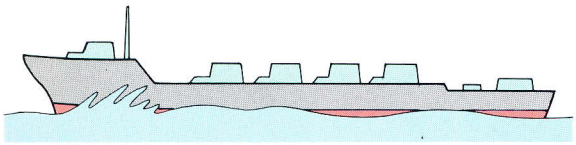
Harnessing the tides

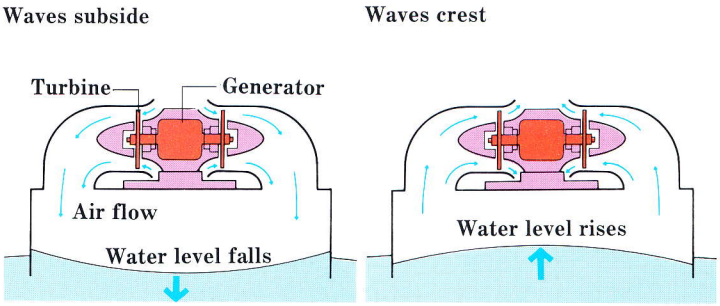
The turbine in a tidal power generating station produces electricity whether the tide is coming in (*below, left*) or going out (*below, right*).



Capturing the power of waves

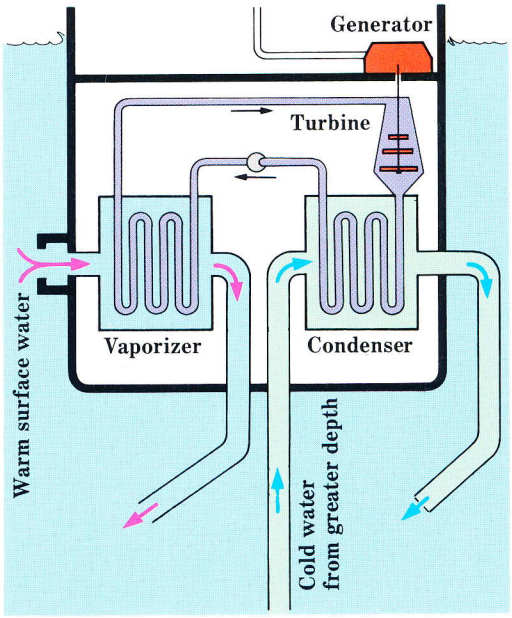
Wave water falling (*right*) under the bell of a floating wave-power generator pulls air in past twin turbine blades. Cresting water (*far right*) expels air, spinning the turbines the other way. The ship is a platform for such generators.





Thermal energy from the ocean

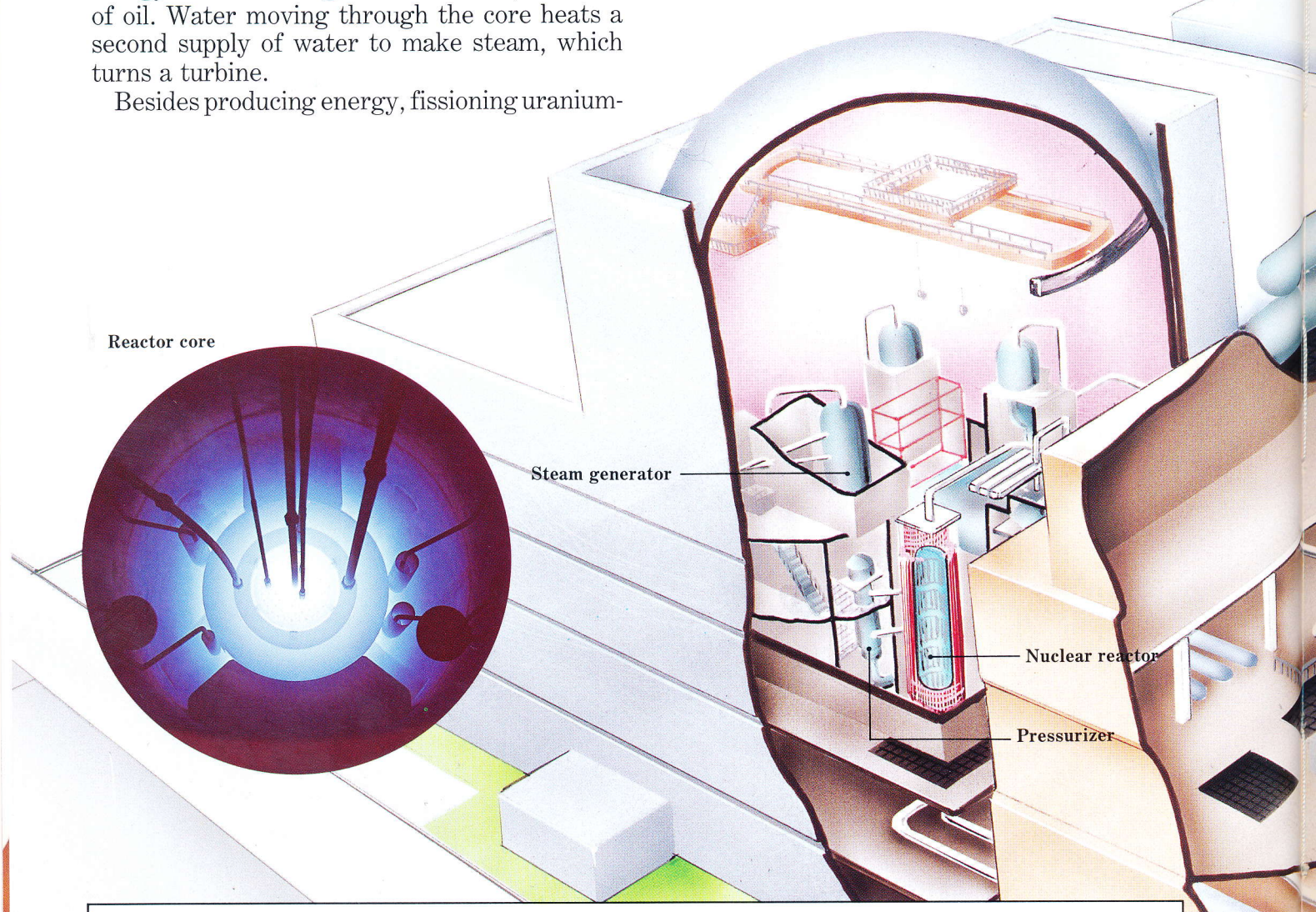
Surface water is warm enough to vaporize a liquid with a low boiling point, such as ammonia. The chemical steam turns a turbine, then condenses as it flows past cold water.



How does a nuclear reactor work?

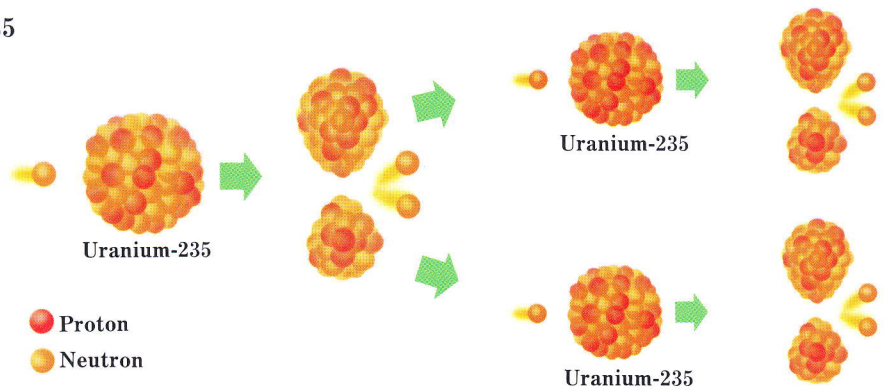
The radioactive core of a nuclear-powered reactor—the most concentrated form of energy used today—sits in a steel tank with 15-centimetre-thick walls. The core contains uranium-235 in the form of 1.25-centimetre pellets stacked inside dozens of 3-metre-long stainless steel tubes. The atoms of uranium-235 undergo fission—that is, they split apart—and every atom that splits releases tremendous amounts of energy. The fission of 1 gram of uranium-235 releases as much energy as the burning of more than 1,900 litres of oil. Water moving through the core heats a second supply of water to make steam, which turns a turbine.

Besides producing energy, fissioning uranium-235 atoms release neutrons, one of two main types of particles in the atomic nucleus. The neutrons strike other uranium-235 atoms, splitting them and releasing still more neutrons to produce a chain reaction, a continuous energy source. To control this chain reaction, rods of boron or cadmium—materials that absorb neutrons—are lowered into the core.



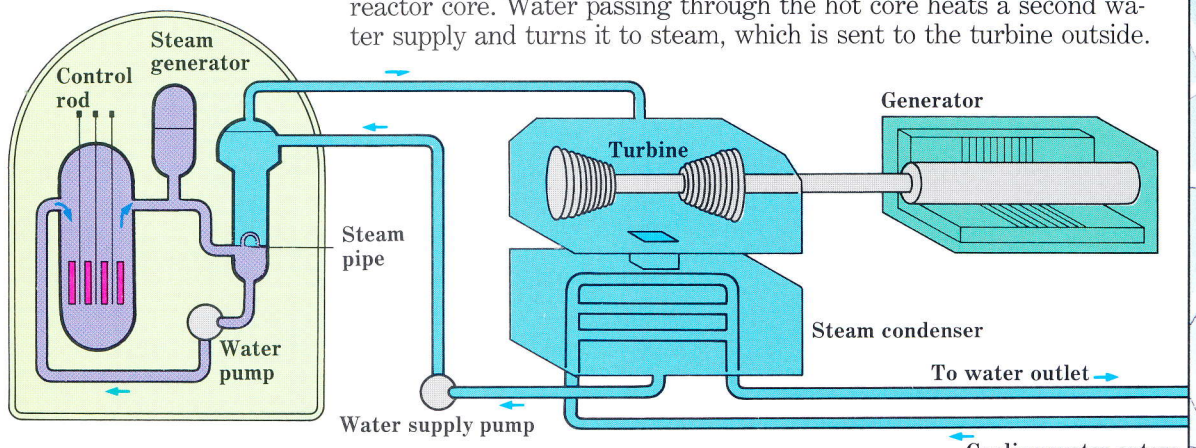
Chain reaction of uranium-235

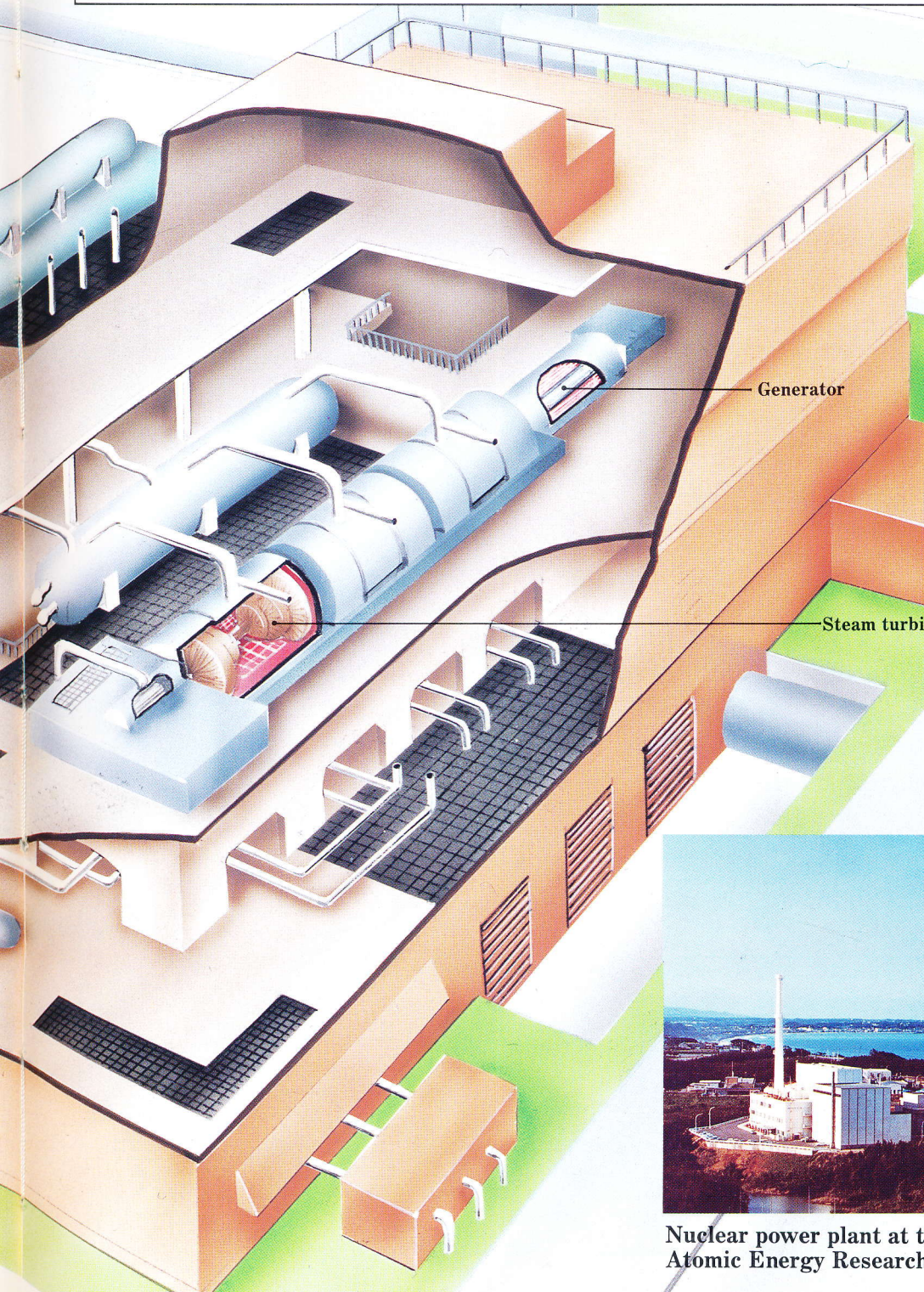
An atom of uranium-235 becomes unstable and splits into two smaller atoms when struck by a neutron. This is nuclear fission. When uranium-235 splits, it releases two or three neutrons that can strike other atoms of uranium-235, starting a self-perpetuating chain reaction.

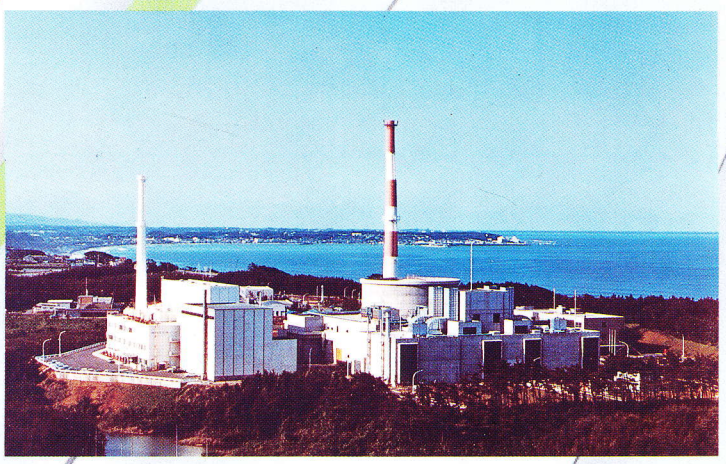


Nuclear power

Nuclear fission releases tremendous amounts of energy within the reactor core. Water passing through the hot core heats a second water supply and turns it to steam, which is sent to the turbine outside.







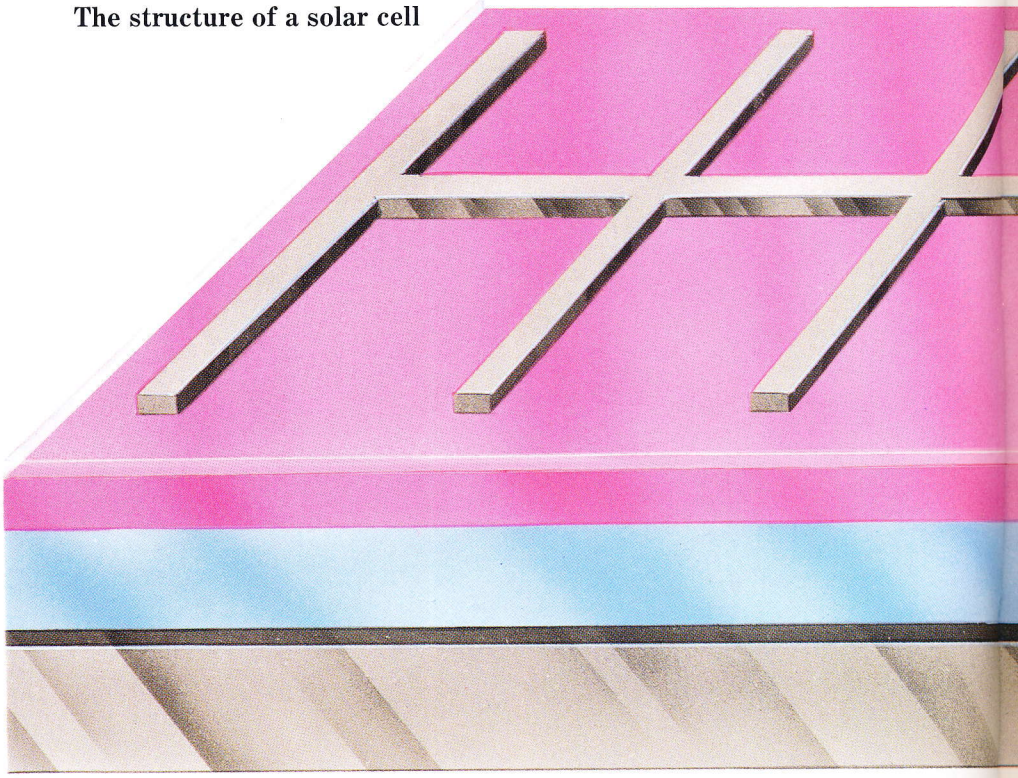
Nuclear power plant at the Japan Atomic Energy Research Institute

How is solar power generated?

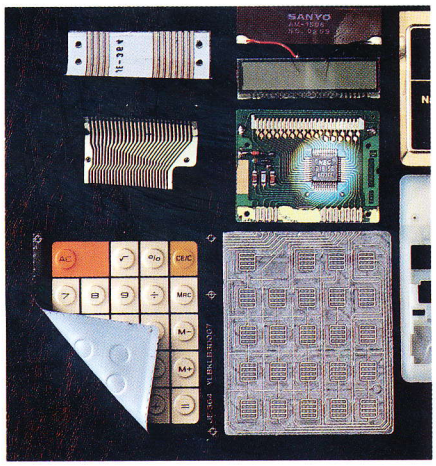
Sunlight, the energy source that makes all life possible, may someday furnish much of the electricity on which modern society runs. Sunlight can be used indirectly to power a turbine. A set of mirrors focuses the sun's energy onto a heat exchanger, which vaporizes water or some other liquid, producing steam to drive a conventional turbine and generator. Silicon solar cells, however, generate electricity directly from sunlight.

A typical solar cell consists of six layers. The base doubles as the cell's negative pole; a reflective layer keeps light within the working part of the cell, boosting the cell's electrical output. Two layers of treated silicon—N-type and P-type—form the heart of the solar cell. N-type silicon has free negative charges and P-type silicon has unbound positive charges. In darkness, the charges gather at the junction between layers; when sunlight hits the cell, they move apart. This movement creates a direct current when the cell is part of a circuit. A clear film protects the silicon, and a metal positive pole completes the cell.

The structure of a solar cell

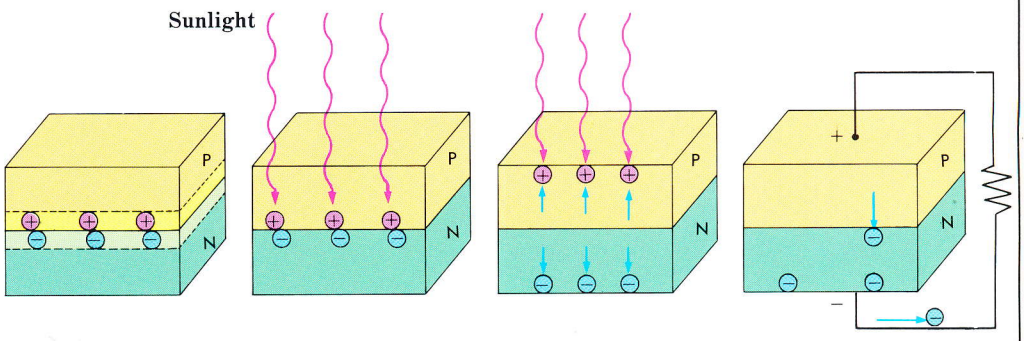


The solar battery in a calculator can run on ordinary room lights.



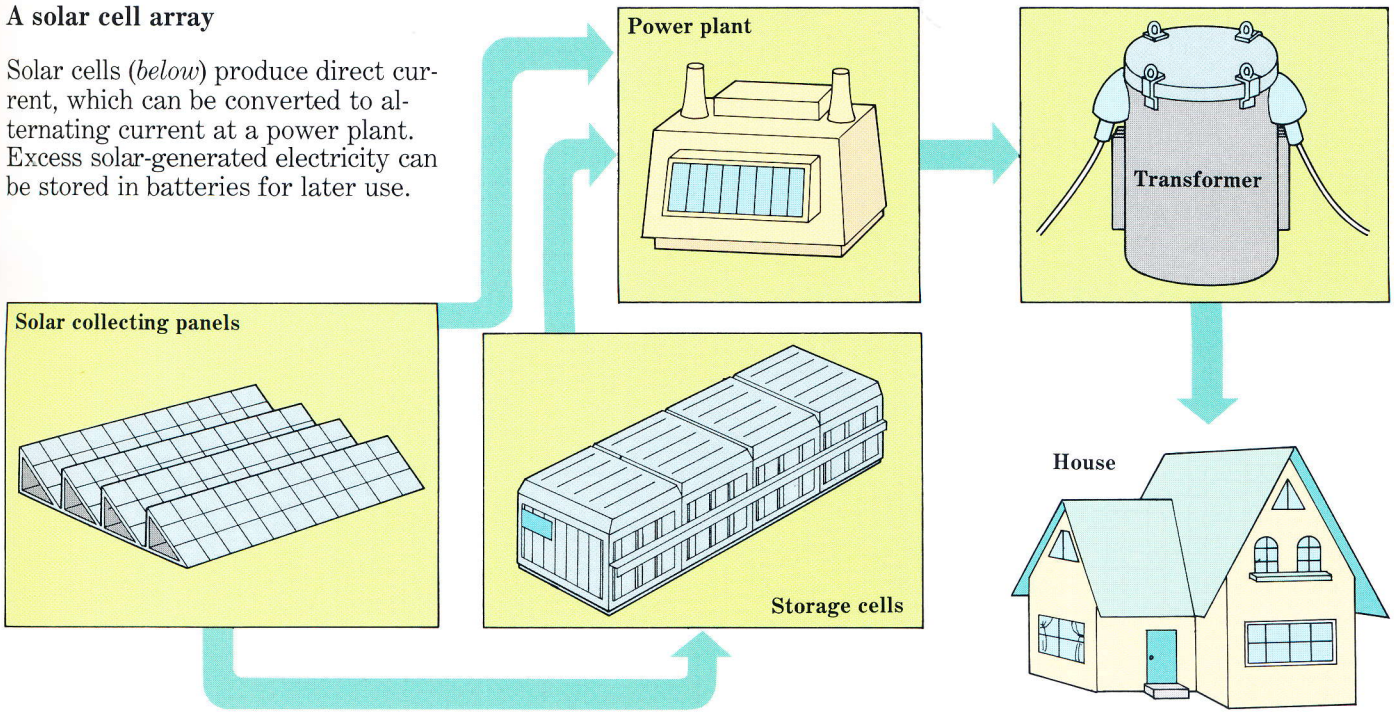
How a solar cell works

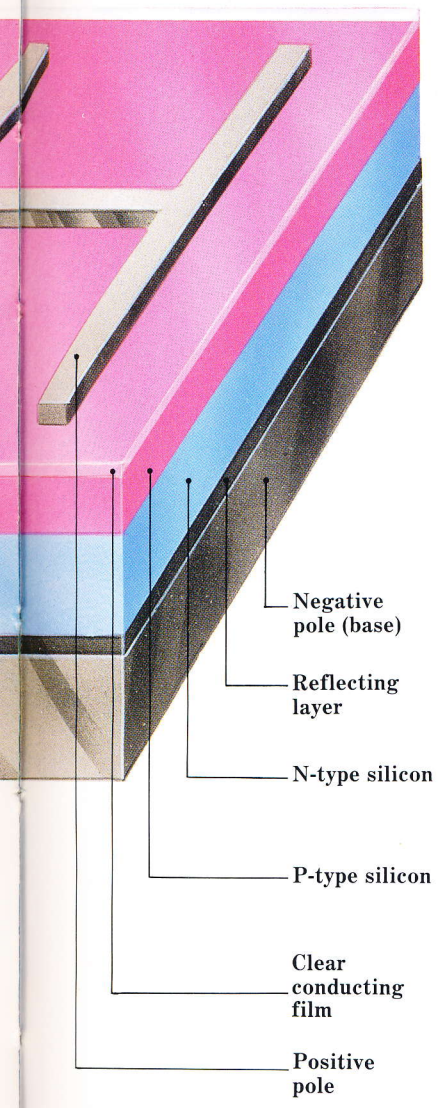
Sunlight striking a solar cell separates the positive and negative charges that accumulate at the junction between slabs of P-type and N-type silicon. The separation creates a voltage that generates a current when the cell is part of a complete circuit.



A solar cell array

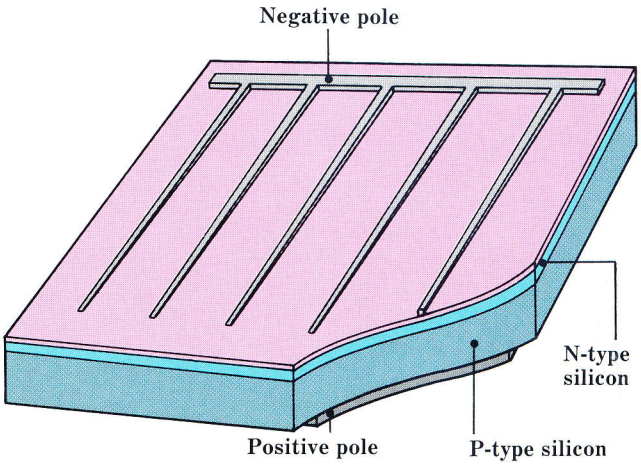
Solar cells (*below*) produce direct current, which can be converted to alternating current at a power plant. Excess solar-generated electricity can be stored in batteries for later use.





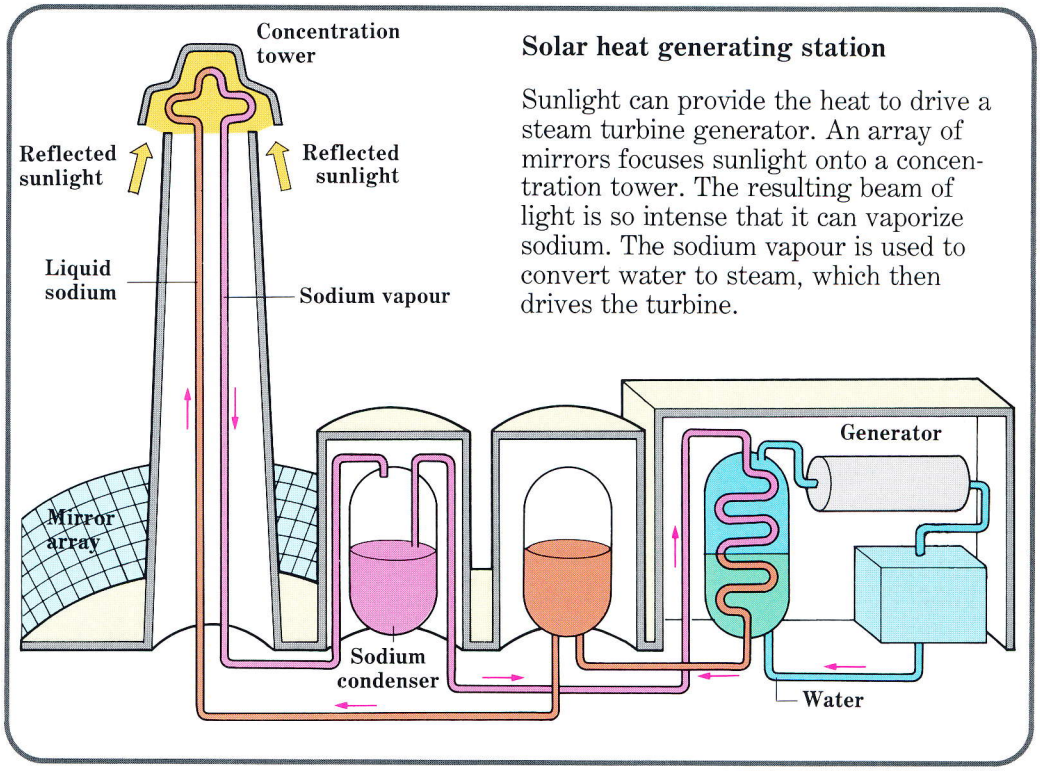
Solar batteries in space

Solar cells have been the prime energy source for most space satellites. These cells (*right*) differ from those used on Earth (*left*). While Earth-bound solar cells need protection from rain and dirt, those that function in space must resist high-energy radiation.



Solar heat generating station

Sunlight can provide the heat to drive a steam turbine generator. An array of mirrors focuses sunlight onto a concentration tower. The resulting beam of light is so intense that it can vaporize sodium. The sodium vapour is used to convert water to steam, which then drives the turbine.



7

The mysteries of light

Almost everything scientists know about the universe comes from observing and analysing light. Yet little was known about light itself until fairly recently. In the seventeenth century, two compelling theories about the nature of light emerged. The corpuscular theory, championed by Sir Isaac Newton, held that light consisted of tiny particles called corpuscles. Another theory proposed that light was a wave, moving through space in much the same way that ripples move across a pond. Although nearly every discovery about light's behaviour during the next 200 years seemed to support the wave theory and discredit the corpuscular theory, the advent of quantum physics in the twentieth century reconciled the two theories: Depending on how it is measured and observed, light may assume the characteristics of either a particle or a wave.

Light has five distinct properties: propagation, reflection, refraction, diffraction, and interference. Propagation refers to the transmission of light in straight lines. Reflection causes light to bounce off polished surfaces such as mirrors. Light refracts, or bends, when it travels from one substance to another, for example from air through a glass lens. Light waves also will bend around an obstacle's edges, a phenomenon known as diffraction. In interference, intersecting light waves alter each other as they meet. Taken together, these properties explain the workings of devices as varied as magnifying glasses, lasers, and holograms.

The dazzling brilliance of lasers illustrates one of the many ways scientists can control light. Lasers amplify a single wavelength of light to produce a powerful, tightly focused beam that is useful in medicine, industry, and communications.

How do curved surfaces affect light?

Light reflects differently off shiny surfaces depending on their curvature. The bowl of a spoon, for instance, gives upside-down reflections, while the spoon's back reflects images the right way up. The determining factor in the reflection's position is the shape of the reflector. Concave surfaces, such as the inner surface of a hollow sphere or the spoon's bowl, often produce inverted images. Convex surfaces, such as the exterior of a sphere or the back of the spoon, produce reflections the right way up.

Concave mirrors reflect light rays inward, directing them to a single spot called the focal point. The rays cross at the place where the image forms. If the object being reflected by a concave mirror lies closer to the mirror than does the focal point, the resulting image will be the right way up. If the object lies beyond the focal point, its reflection will be inverted. Reflections from a convex surface, however, are always the right way up because such surfaces cause reflected light rays to diverge rather than converge. As a result, the reflected rays never cross each other to produce an inverted image.

1

Key:

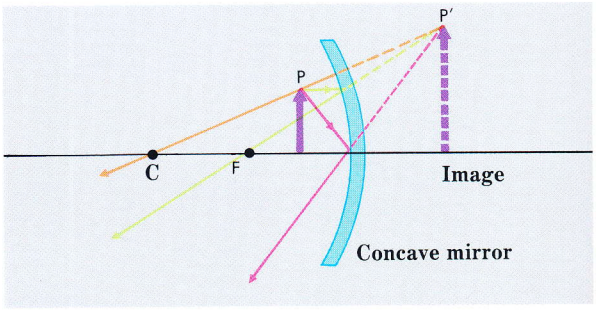
P = Object

P′ = Image

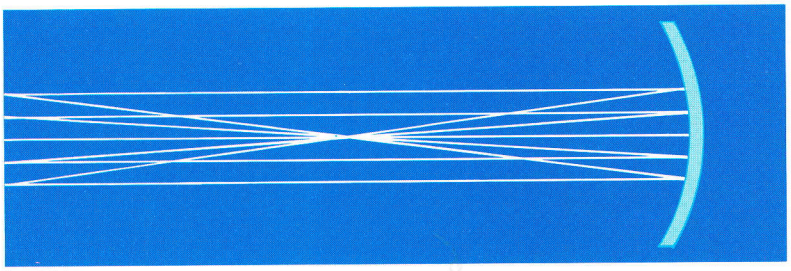
C = Centre of sphere

F = Focal point

1

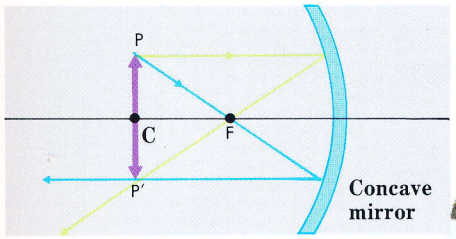


A larger-than-life image (P′) of the panda (*above*) appears in a spherical, concave mirror when the panda (P) is between the mirror and the focal point (F). The image forms where reflected rays cross.



Parallel rays converge at the focal point as they reflect off the concave surface of a spherical mirror.

3



The reflection is still inverted but looks life-size when the panda sits at the centre of the spherical mirror.

3

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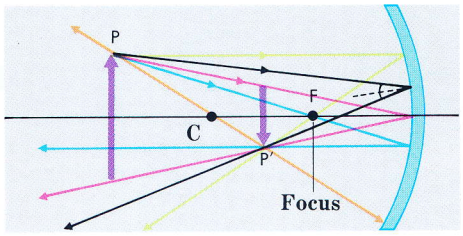
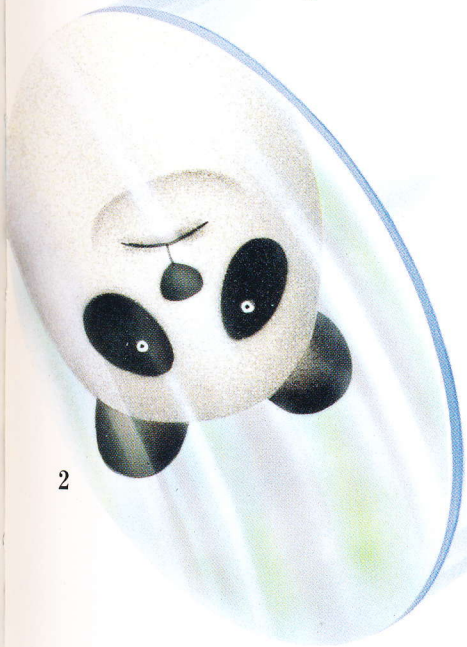


The inverted reflection shrinks as the panda moves away from the centre of the mirror.



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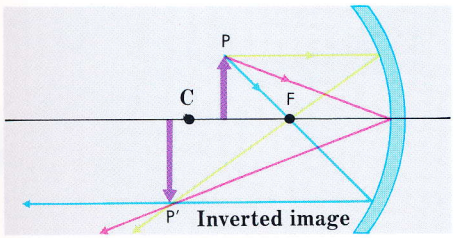
2



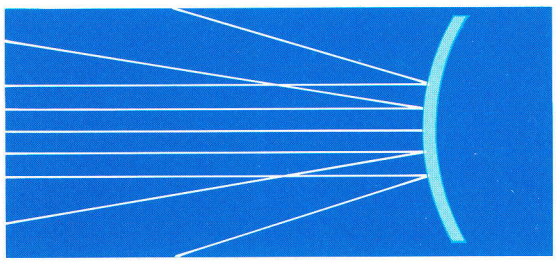
An upside-down but still larger-than-life image appears when the panda sits between the focal point and the centre of the sphere.

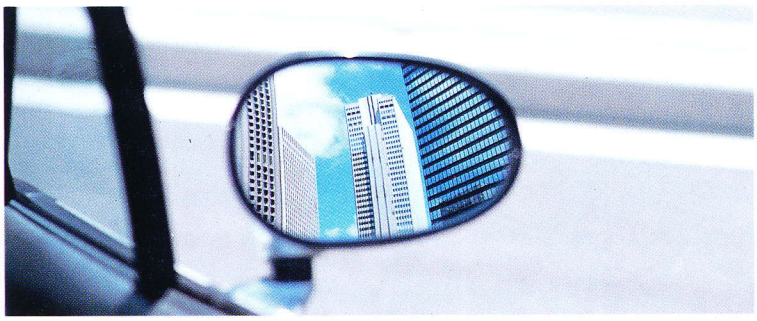
Faces in a spoon

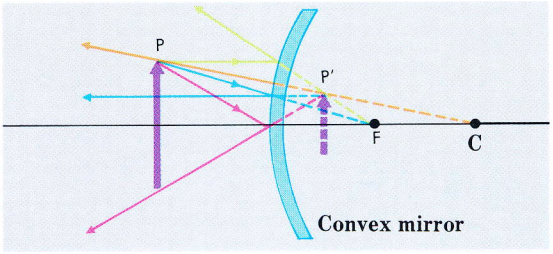
The inner and outer surfaces of a spoon act like the concave and convex surfaces of a spherical mirror. Because the focal point of the spoon's bowl is so close to the spoon, the reflected face will always be upside down. The convex back of the spoon always yields a reflection that is smaller and the right way up.

Images in a convex mirror

An image reflected by a convex mirror is always the right way up and small no matter how far away the object is. Because convex mirrors generate a wider field of view (*right*) than do flat mirrors, they are useful as rear-view mirrors in cars.

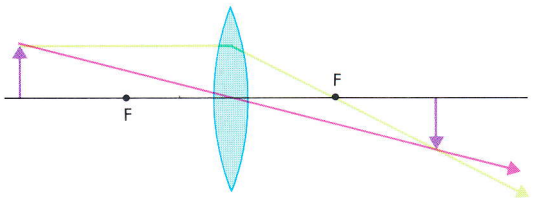




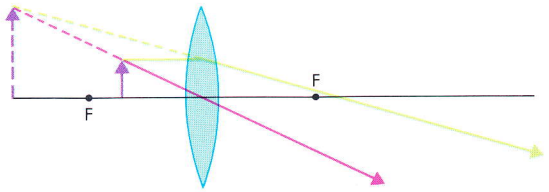


How does a magnifying glass work?

A magnifying glass consists of a double convex lens, which curves outward on both sides. Rays of light passing through the lens bend inward, converging at a focal point on either side of the lens. The distance from the centre of the lens to the focal point, about 12 centimetres for a typical magnifying glass, is called the focal length. When a magnifying glass is held over an object at a shorter distance than the focal length, the object appears the right way up and magnified. This kind of image is called a virtual image. At a distance equal to or longer than the focal length, the lens produces an inverted image, called a real image.

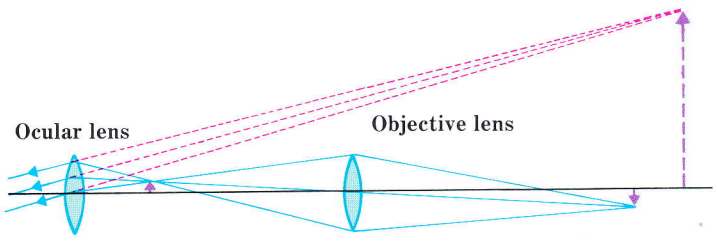


At a distance of twice the focal length from the lens, the object (*purple arrow pointing upward*) appears as a real image that is life-size but inverted.



When an object (*solid arrow*) is closer to the lens than the focal point (F) is, the lens creates a virtual image (*purple dashes*) that is the right way up and magnified.

Convex lenses



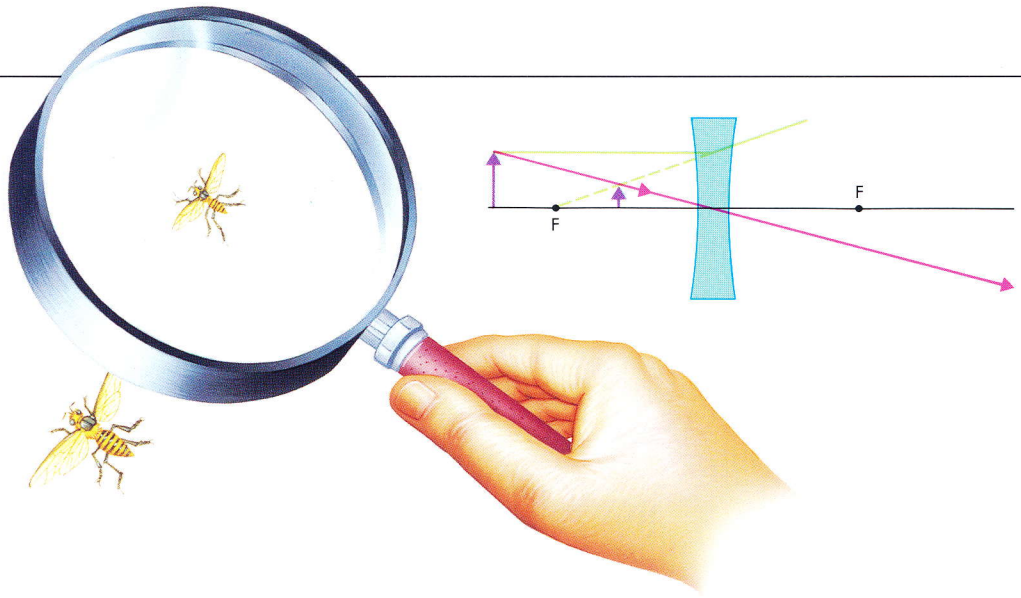
Many telescopes use two double convex lenses, called the objective and the ocular lenses. The objective lens creates a virtual image that is magnified for viewing by the ocular lens.

A convex lens magnifies objects, while a concave lens shrinks them.

If the object lies beyond twice the focal length, the bee looks inverted and small.

Concave lenses

When the double convex lens is replaced by a double concave lens—in which both sides curve inward—a magnifying glass becomes a demagnifying glass. The double concave lens creates images that are the right way up and smaller than the actual object.

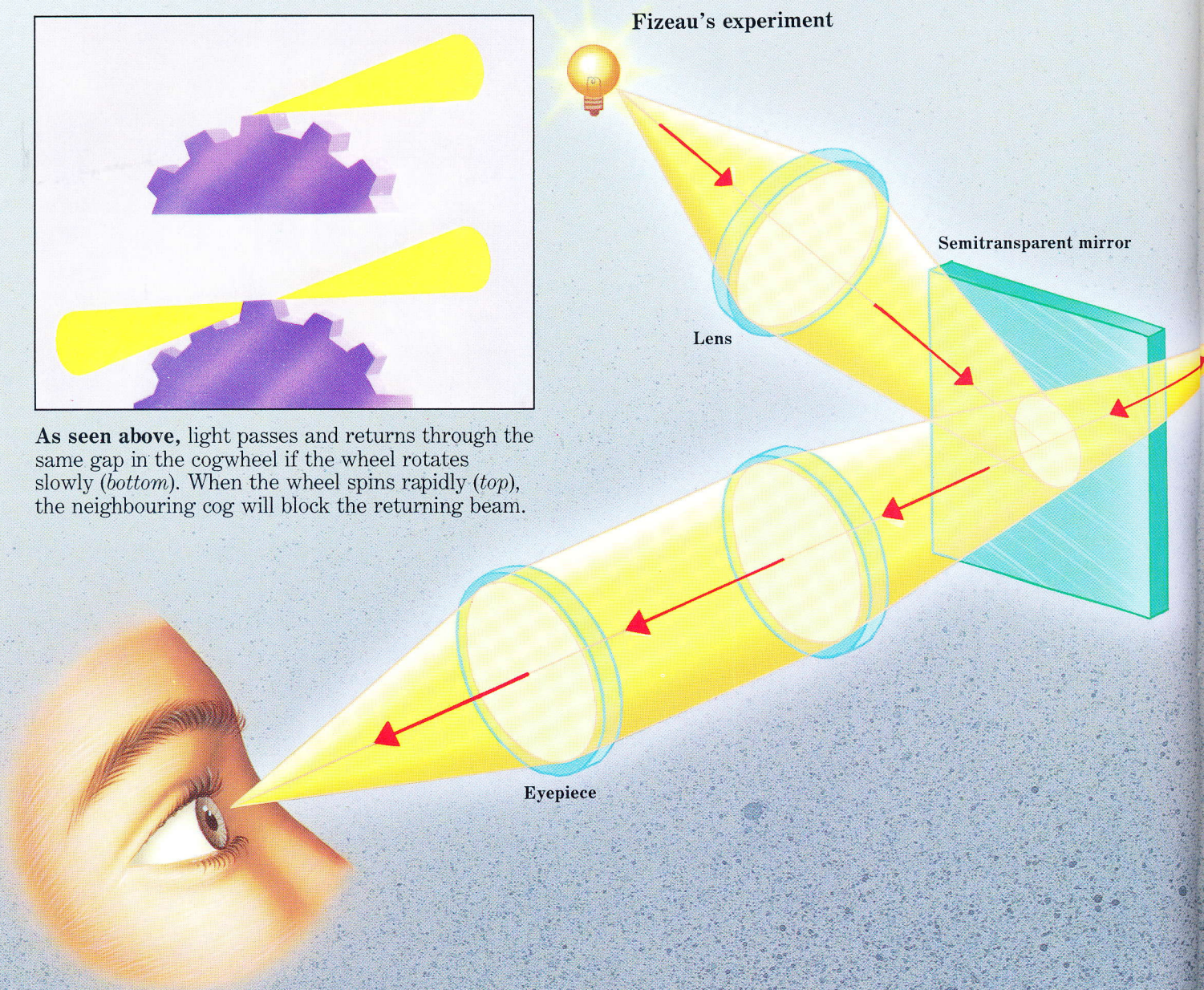


How is the speed of light measured?

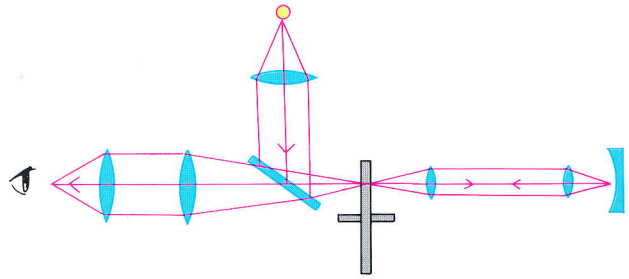
In 1676, Danish astronomer Ole Rømer made the first rough estimate of the speed of light. Rømer noticed a slight discrepancy in the duration of eclipses of the moons of Jupiter and concluded that the motion of Earth, either approaching or receding from Jupiter, changed the distance that the light from the moons had to travel. From the discrepancy, he concluded that the speed of light was 219,904 kilometres per second. In a later experiment in 1849, French physicist Armand Fizeau measured the speed of light as 312,864 kilometres per second.

As illustrated below, Fizeau's experiment consisted of a light source, a semitransparent mirror —which reflects only half the light that strikes it, allowing the rest to pass through—and a rotating cogwheel and stationary mirror. As light struck the semitransparent mirror, it reflected toward the cogwheel, which sliced it into beams. Kept in tight focus by lenses placed along its path, each beam reflected off the stationary mirror and back toward the cogwheel. By measuring the precise speed at which the cogwheel blocked the beams, Fizeau could calculate the speed of light. His colleague Jean Foucault refined this method a year later, arriving at a speed of light of 297,870 kilometres per second. This figure was close to the modern value of 299,792 kilometres per second, which is calculated by multiplying the wavelength and frequency of a laser beam.

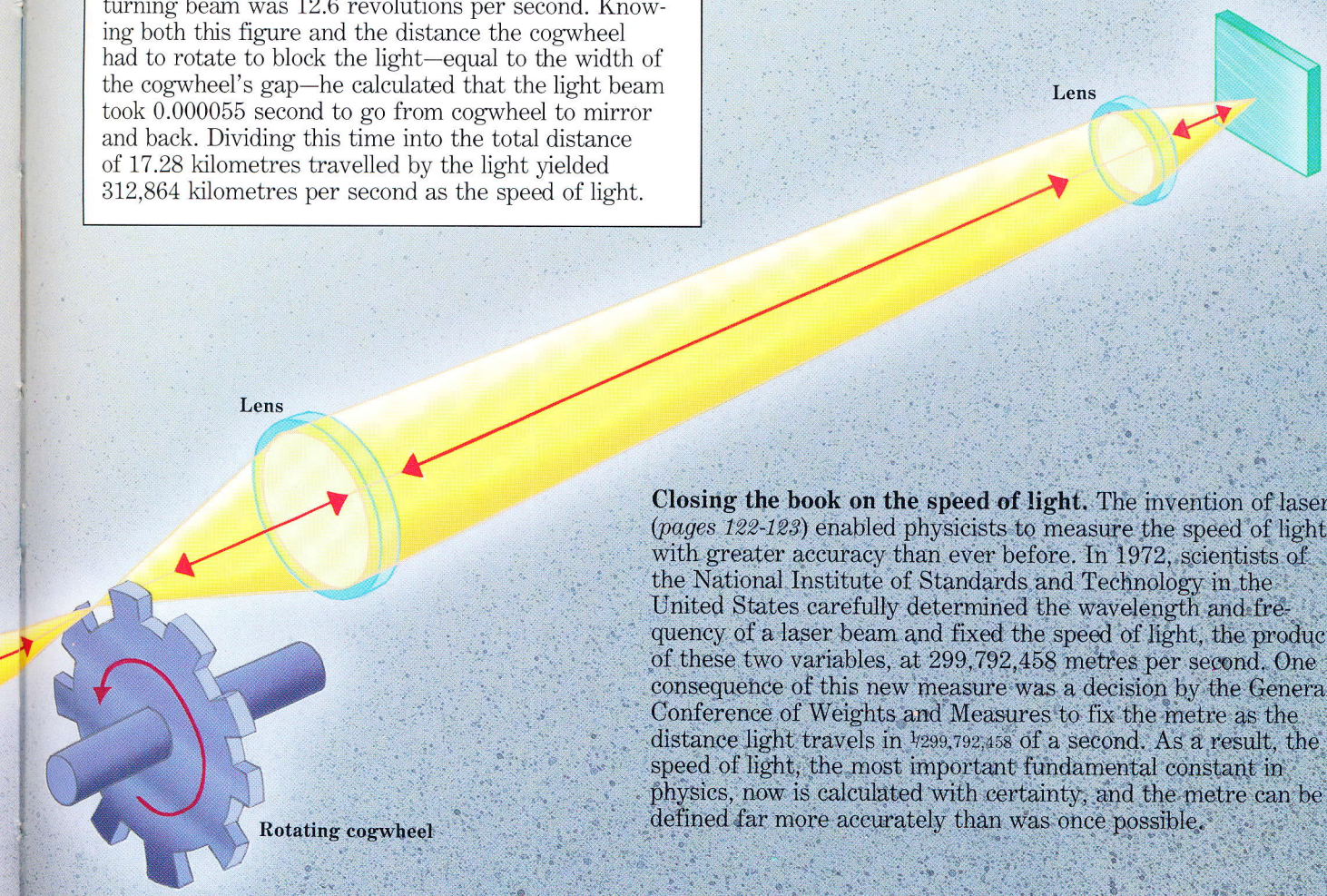
As seen above, light passes and returns through the same gap in the cogwheel if the wheel rotates slowly (*bottom*). When the wheel spins rapidly (*top*), the neighbouring cog will block the returning beam.



Fizeau's results



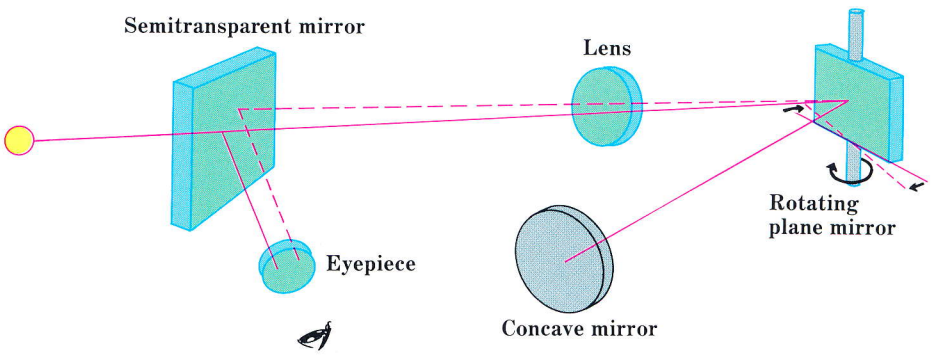
When Fizeau placed the mirror 8.64 kilometres away, the cogwheel rotation speed necessary to block the returning beam was 12.6 revolutions per second. Knowing both this figure and the distance the cogwheel had to rotate to block the light—equal to the width of the cogwheel's gap—he calculated that the light beam took 0.000055 second to go from cogwheel to mirror and back. Dividing this time into the total distance of 17.28 kilometres travelled by the light yielded 312,864 kilometres per second as the speed of light.



Closing the book on the speed of light. The invention of lasers (*pages 122-123*) enabled physicists to measure the speed of light with greater accuracy than ever before. In 1972, scientists of the National Institute of Standards and Technology in the United States carefully determined the wavelength and frequency of a laser beam and fixed the speed of light, the product of these two variables, at 299,792,458 metres per second. One consequence of this new measure was a decision by the General Conference of Weights and Measures to fix the metre as the distance light travels in $^{1}/_{299,792,458}$ of a second. As a result, the speed of light, the most important fundamental constant in physics, now is calculated with certainty, and the metre can be defined far more accurately than was once possible.

Foucault's experiment

In 1850, French physicist Jean Foucault modified Fizeau's technique by substituting a rotating mirror for the cogwheel. Only when the mirror makes a complete 360° revolution between the time of the light beam's departure and return does an observer detect any light from the source. This method let Foucault calculate a value of 297,870 kilometres per second for the speed of light.

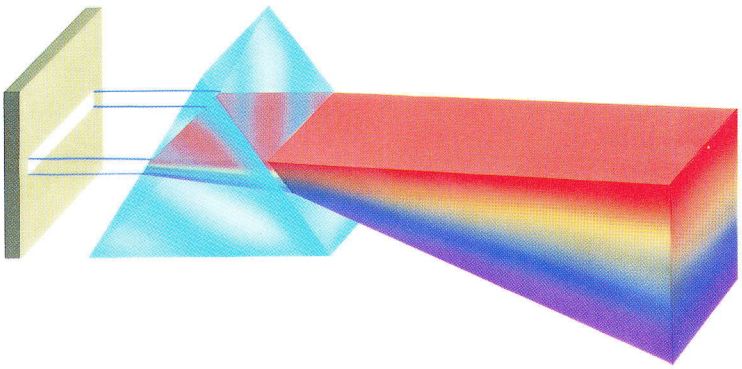


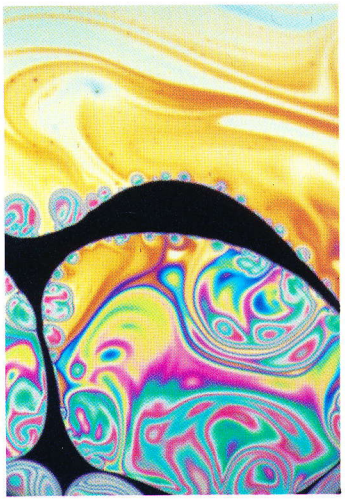
Why are soap bubbles so colourful?

The kaleidoscope of colours swirling across a soap bubble is caused by the complex nature of light and the way it reflects off the bubble's surface. White light consists of an array of colours, each characterized by a different wavelength, shown at right as waves with crests and troughs. When light strikes the surface of a soap bubble, some light waves immediately reflect off the bubble. Other waves penetrate the film of the bubble itself, where they bend and reflect off the inner surface. When these waves encounter waves bouncing off the outer surface, their crests and troughs are not always aligned. When crests and troughs match up, the waves combine to amplify—that is, brighten—the reflected light. But when they do not match, they weaken each other in so-called wave interference. In such a case, a rainbow appears on the soap film because varying thicknesses in the film cause interference patterns and reflect light in the different wavelengths of each colour.

The spectrum of white light

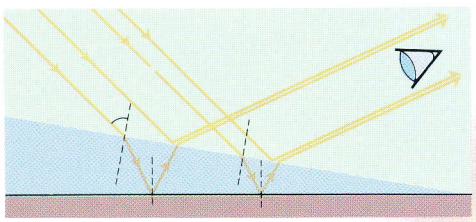
When white light passes through a prism (*below*), the light breaks into its component colours, the familiar red, orange, yellow, green, blue, indigo, and violet of the rainbow. Shorter wavelengths refract at greater angles than longer wavelengths. Violet, with the shortest wavelength, bends the most, while red, with the longest wavelength, bends least.



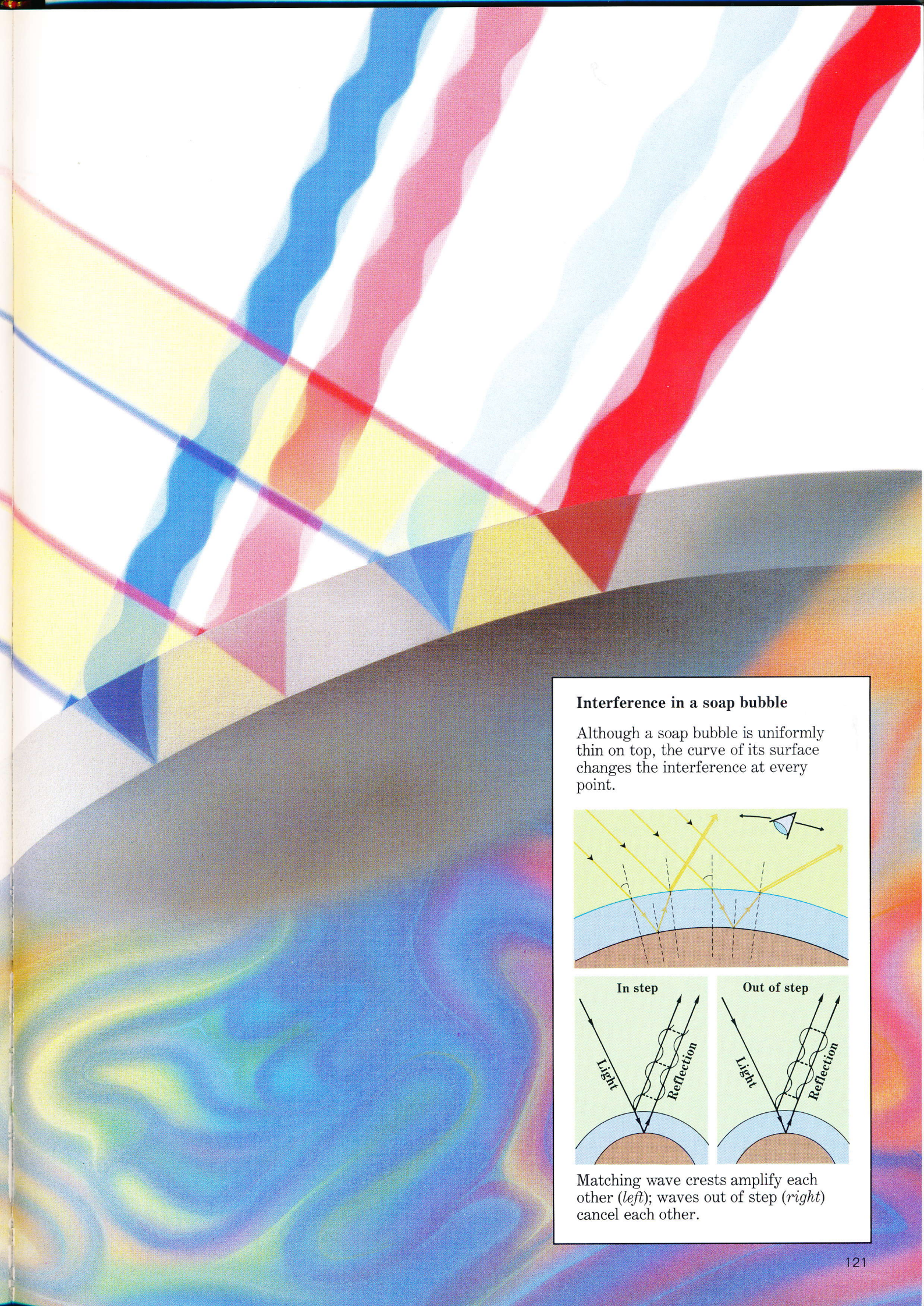


Interference in a film of oil

On a thin oil film, colours result from interference, depending on the film's thickness and the angle at which the light strikes (*below*). Black appears where all light waves cancel each other out.



Swirls of colour appear on an oil film.



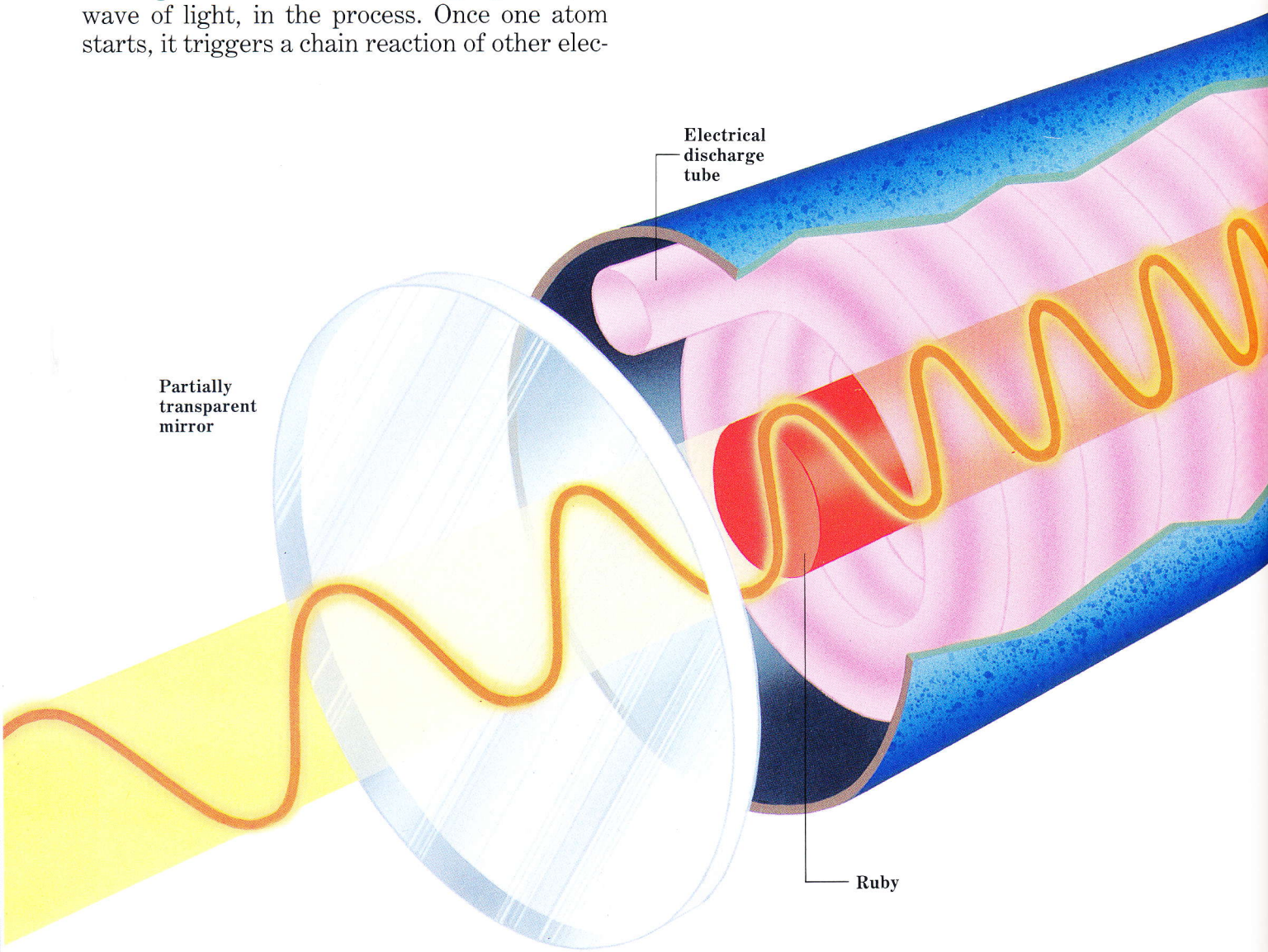
Interference in a soap bubble

Although a soap bubble is uniformly thin on top, the curve of its surface changes the interference at every point.

Matching wave crests amplify each other (*left*); waves out of step (*right*) cancel each other.

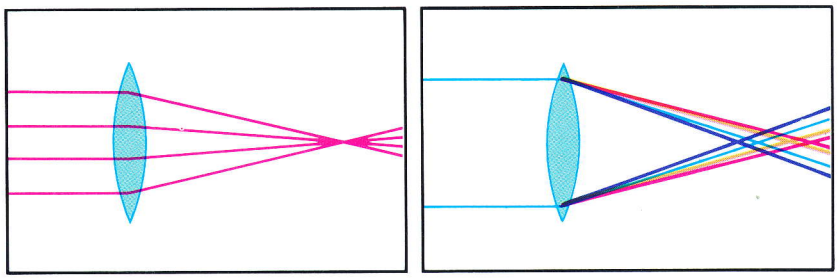
What is a laser?

The laser is a device that produces a narrow beam of intense light. Lasers exploit the fact that the electrons in an atom can occupy only specific orbits around their nucleus. When an atom receives a jolt of energy, it can become excited, pushing its electrons from the lowest energy orbit, called the ground state, to one of higher energy. But the electrons cannot stay long in a high-energy orbit and begin to drop back down to the ground state, each emitting a photon, or wave of light, in the process. Once one atom starts, it triggers a chain reaction of other electrons dropping down, resulting in an avalanche of identical light waves perfectly aligned with one another. These waves form a powerful beam that in some lasers grows strong enough to cut through stone and metal. Invented in 1960, lasers are used in fields as varied as medicine and music to vaporize tumours or to etch and read the signals on compact discs.

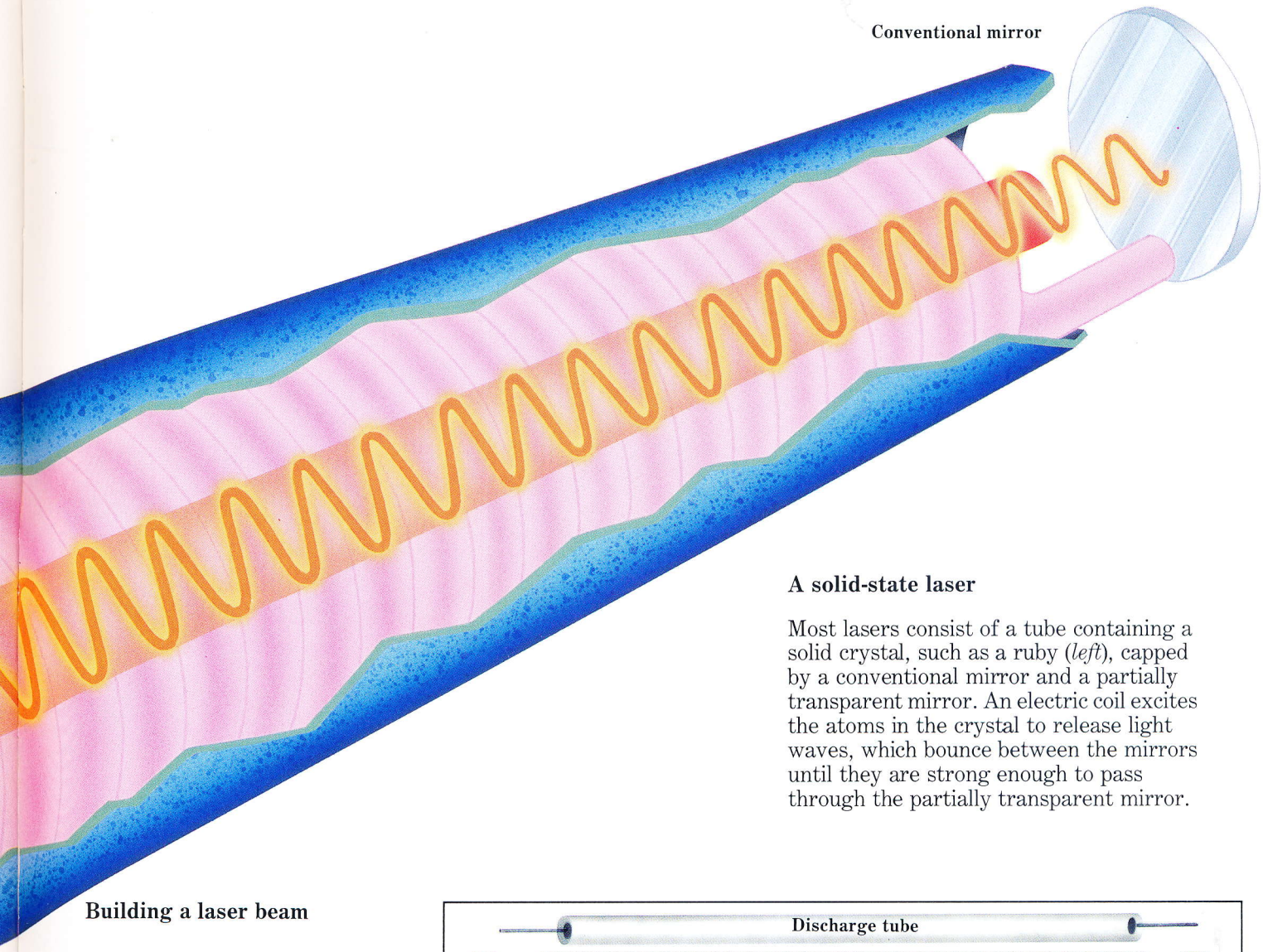


A sharper focus

A laser beam contains just one wavelength of light and can be tightly focused at a single point by a lens (*right*). Natural light with several wavelengths does not focus as sharply (*far right*). What makes the laser an important tool is its ability to focus a lot of energy on a tiny spot and to travel long distances at low power without spreading and weakening as multicoloured light does.



Laser light (one colour) **Natural light (many colours)**



A solid-state laser

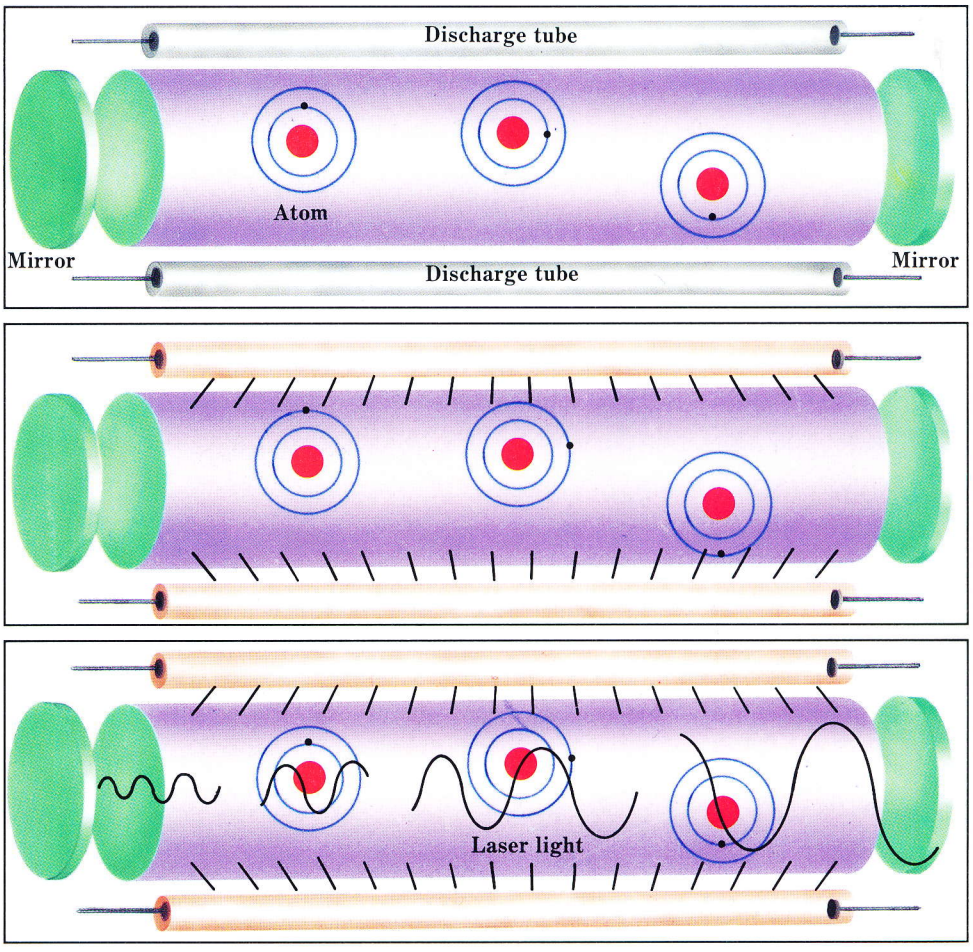
Most lasers consist of a tube containing a solid crystal, such as a ruby (*left*), capped by a conventional mirror and a partially transparent mirror. An electric coil excites the atoms in the crystal to release light waves, which bounce between the mirrors until they are strong enough to pass through the partially transparent mirror.

Building a laser beam

1. The electrons of each atom (*black dots on inner circles, right*) reside in the ground state before the laser is turned on.

2. Once the laser is switched on, energy from the discharge tube pushes the electrons into more energetic orbits (*outer circles*).

3. As electrons start falling back to the ground state, they emit light, prompting other electrons to do the same. The resulting beam has one wavelength and grows more powerful as more electrons drop down.

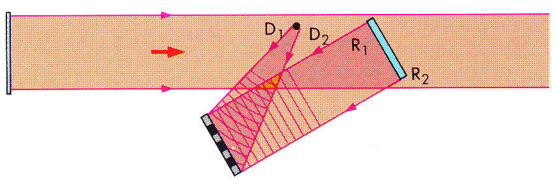


What is a hologram?

A hologram is a photograph that creates a three-dimensional image when light shines on it. The process of making a hologram begins as a semitransparent mirror splits light from a laser into two beams called the object wave and the reference wave. The object wave bounces off the object being photographed and heads toward a special film, while the reference wave bypasses the object and heads directly for the film. When the two waves meet again, they combine on the film to create a unique interference pattern that encodes information about the object in three dimensions. Shining a laser beam on the developed hologram reverses the process as the light unscrambles the interference pattern to reveal the original image carried by the object wave.

Making a hologram

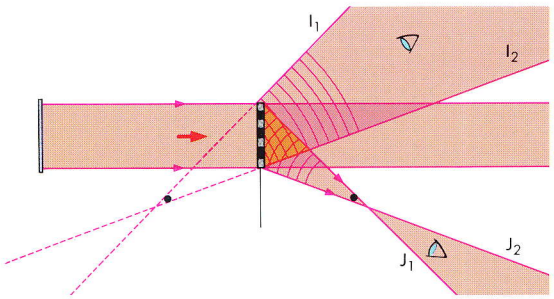
A semitransparent mirror splits a laser into two beams (*below, left*). When rejoined, the beams store the information as an interference pattern on film.



An interference pattern forms as object waves, D_1 and D_2, and reference waves, R_1 and R_2, meet at different angles. Areas of constructive, or mutually strengthening, interference appear in black on the diagram.

Reproducing the image

When laser light of the same wavelength as the object and reference beams shines on the hologram, it diffracts in the same way as it would if it were striking the object itself. In some cases, images from holograms can also be seen in natural light rather than laser light.



A laser shines on the hologram and is diffracted as I_1, I_2 or J_1, J_2 by the interference on the film, re-creating a three-dimensional image.

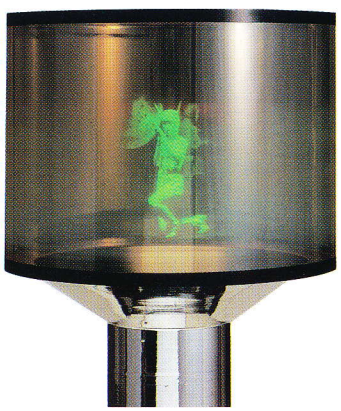
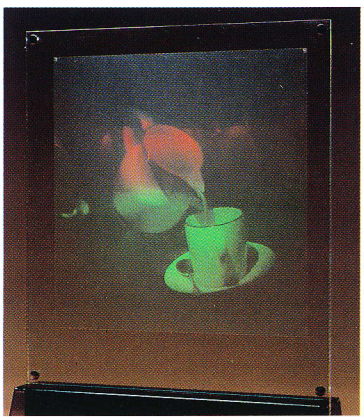


Image in the round



A natural-light image

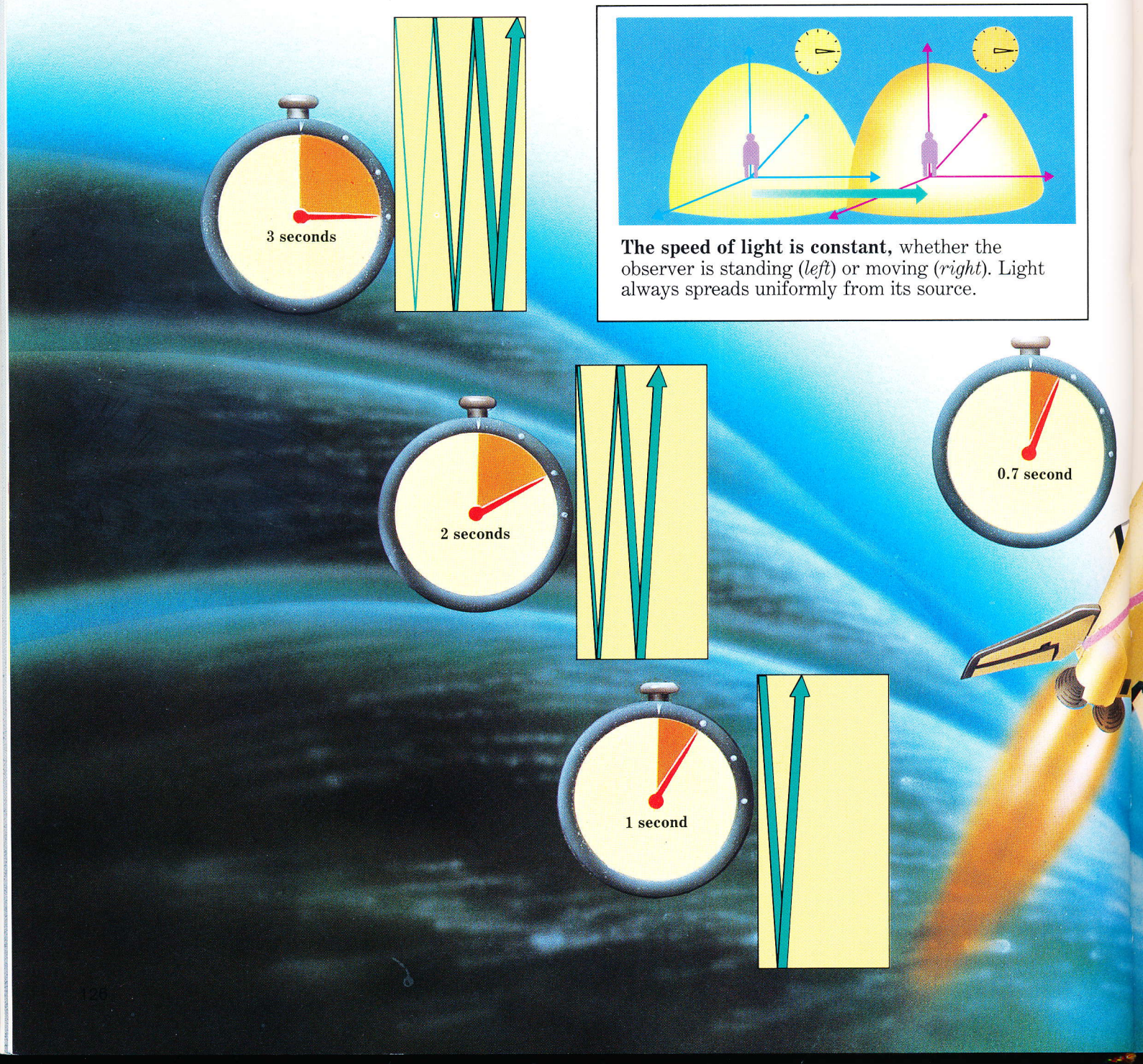
What happens near the speed of light?

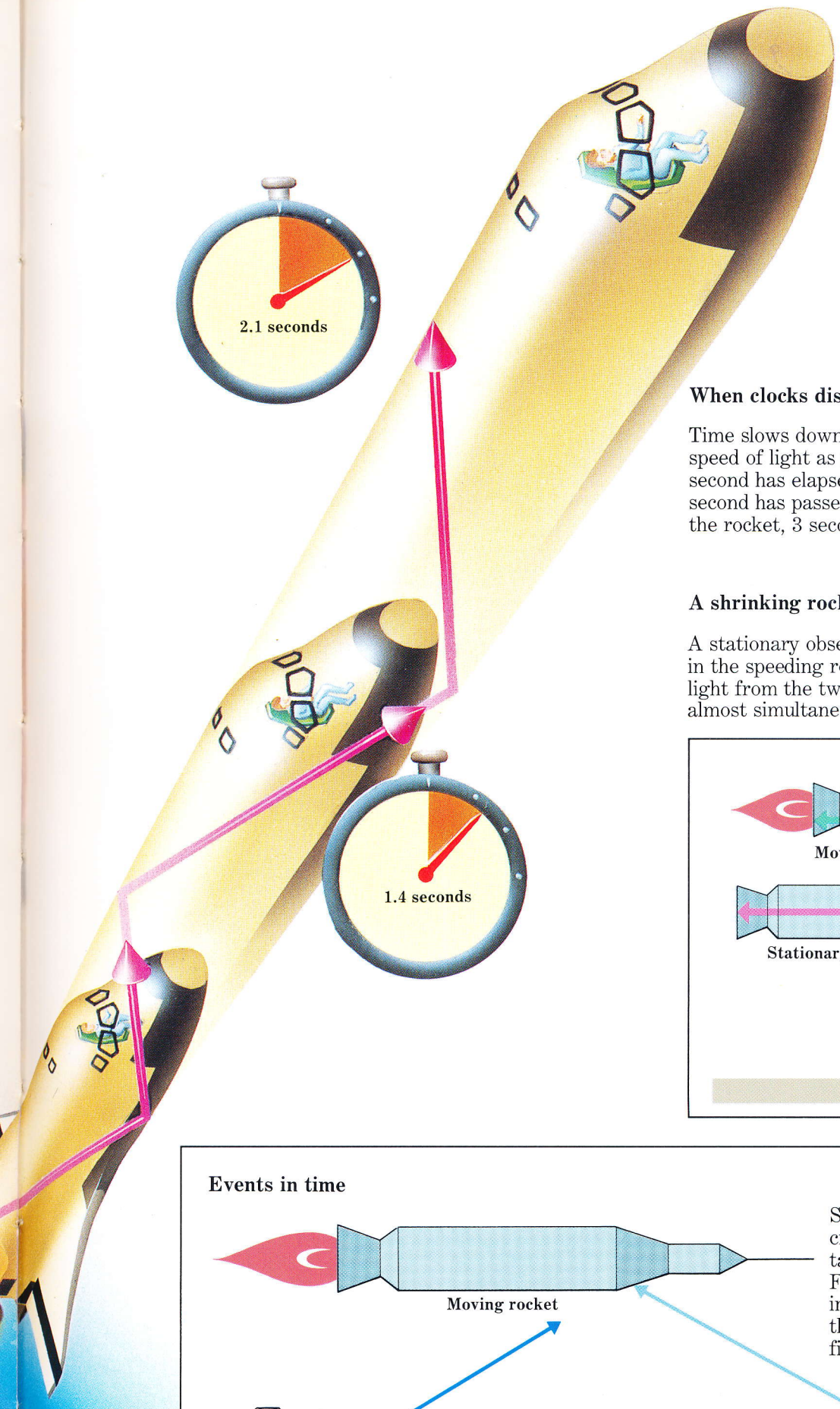
In 1887, American scientists Albert Michelson and Edward Morley performed an experiment that proved the speed of light is constant for every observer. Building on that experiment, Albert Einstein stated in his special theory of relativity two decades later that nothing except light itself can travel at the speed of light, 299,792 kilometres per second. But for objects travelling very close to the speed of light, very strange things would happen. Time would slow down for an object approaching the speed of light relative to time experienced by an observer on Earth. The object's length would shrink, and its mass would increase.

If not for the speed limit imposed by relativity, a rocket travelling at the speed of light would have zero length and infinite mass—all impossible results.

Einstein's theory does have some interesting consequences for future space travellers. Inside a spaceship travelling close to the speed of light everything would seem normal. But to an observer on Earth, the ship would look shorter and its clocks would be slow. Astronauts spending a decade hurtling through space, according to their reckoning, might return to find that a century had passed on Earth.

The speed of light is constant, whether the observer is standing (*left*) or moving (*right*). Light always spreads uniformly from its source.



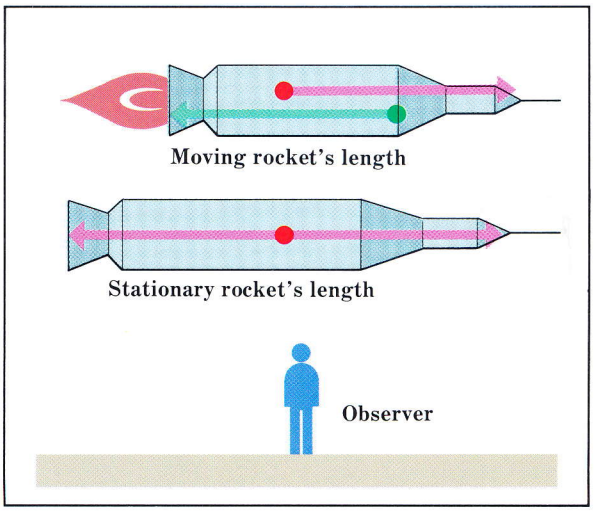


When clocks disagree

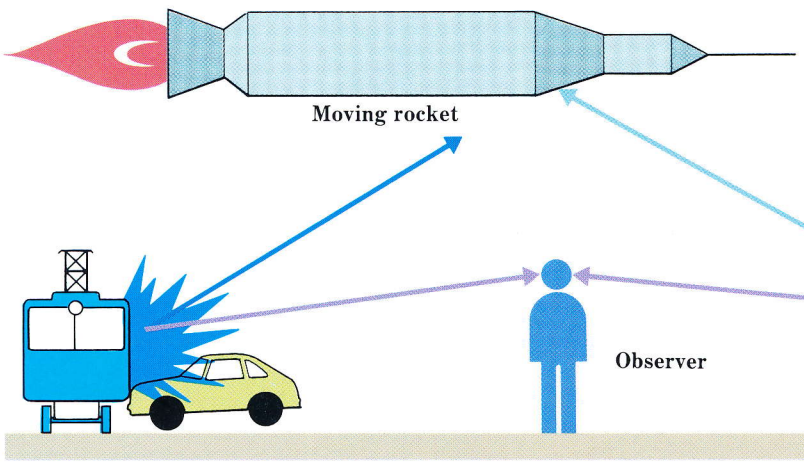
Time slows down on a rocket travelling near the speed of light as monitored from Earth. When 0.7 second has elapsed aboard the rocket, one full second has passed on Earth. After 2.1 seconds on the rocket, 3 seconds have gone by on Earth.

A shrinking rocket

A stationary observer would perceive a decrease in the speeding rocket's length (*top*) because the light from the two ends reaches the observer almost simultaneously.



Events in time



Seen from Earth, the car crash and the fire appear to take place at the same time. From inside the rocket moving near the speed of light in the direction of the fire, the fire seems to happen first.

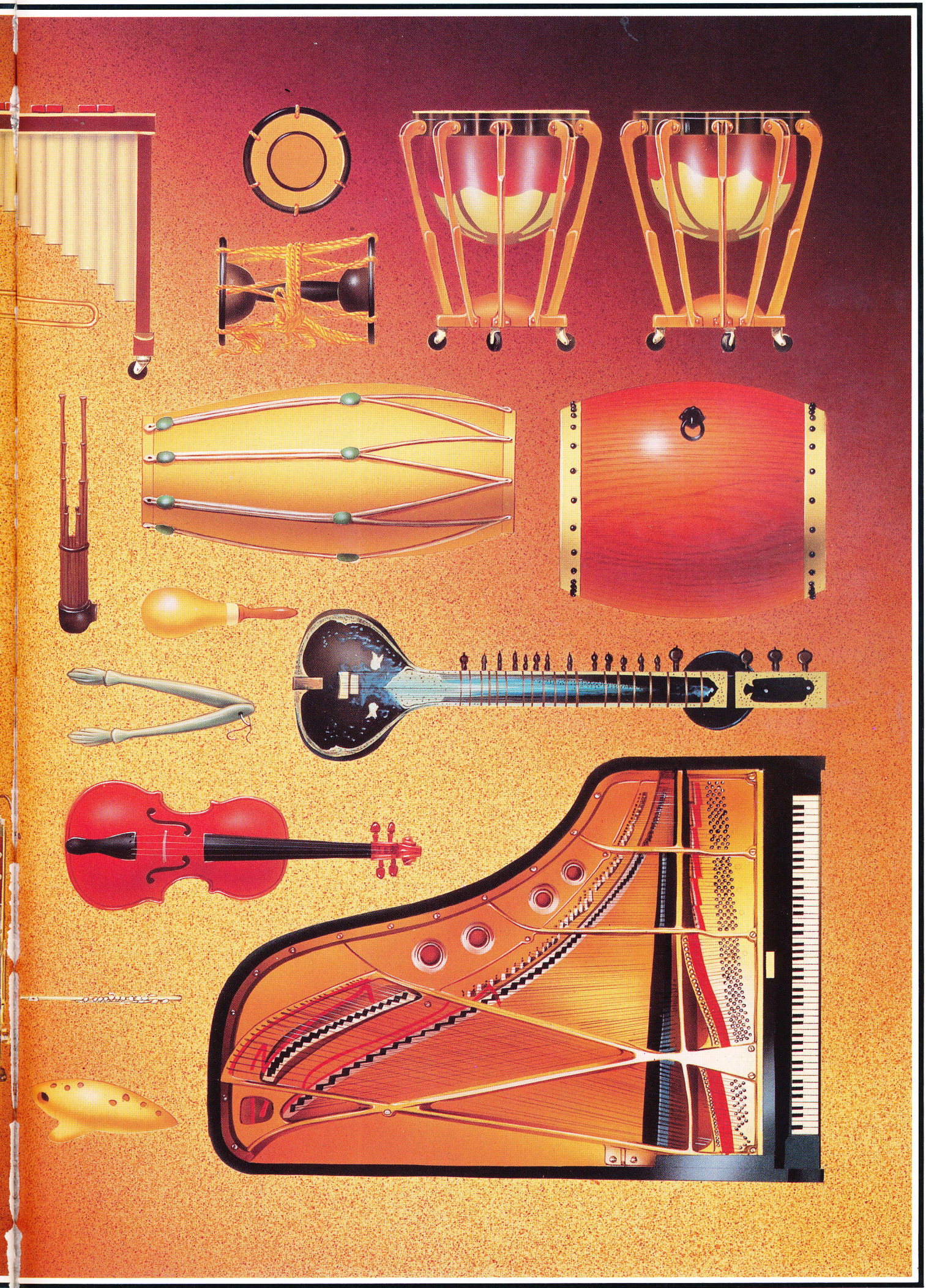
8

The physics of sound

The world is teeming with sounds, ranging from barely audible rumblings to piercing shrieks. Soft or loud, soothing or shattering, the phenomenon of sound gives people invaluable clues about their environment. Sound owes its existence to waves produced by subtle vibrations of an object, such as a snare drum that has been struck. These waves are transmitted through air and other gases, liquids, and solids. When they reach a person's ear, the waves are perceived differently according to their characteristics.

A key factor is frequency, defined as the rate at which successive crests or troughs of a series of waves pass a fixed point in space. Frequency is expressed in terms of hertz, representing a count of one wave cycle per second. Humans can hear sounds in the 20 to 20,000 hertz range. A wave's frequency is related to a sound's pitch, with high-frequency waves yielding high pitch and low frequencies producing low pitch. Scientists measure a sound's intensity, which depends on a wave's inherent energy, with a standard unit called a decibel. Normal conversation registers about 60 decibels, a jet engine 140 to 160. Sounds above 120 decibels may result in damage to the eardrums and possibly a total loss of hearing.

Each instrument shown at right has its own distinctive timbre, or quality of sound. By striking a surface, blowing into a mouthpiece, or plucking or bowing strings, musicians make music, producing sound waves of different pitches.

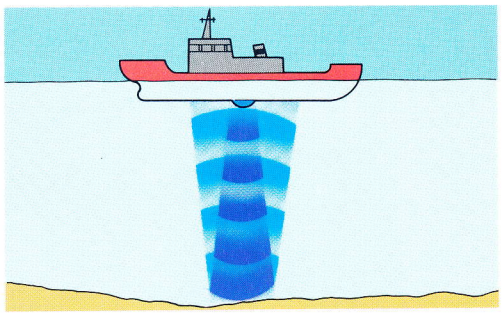


How is sound transmitted?

Sound is transmitted by waves. These waves travel through gases, liquids, and solids alike. Wave action is mainly a transfer of energy. In the case of sound, this transfer takes the form of tiny motions at the molecular level. In gases and liquids, a sound wave shifts molecules slightly in a direction parallel to itself, that is, in a lengthwise direction. In solids, motion may also occur perpendicular to the wave.

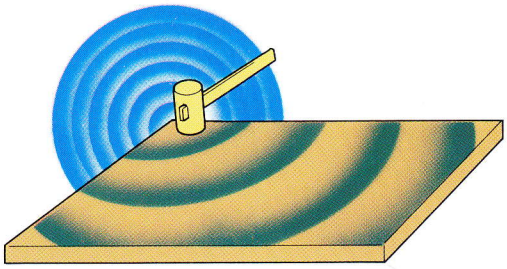
Sound waves spread from their source in all directions, as depicted at right, where a metal bell has been struck by its clapper. This mechanical jarring has made the bell vibrate. The energy of the vibrations stirs surrounding molecules of air, pushing them away from the bell. This slight expansion of the air surrounding the bell results in an increase in pressure, which propagates outward from the source.

The speed of sound is independent of loudness of tone. The sounds from a radio in a room, whether they are loud or soft, of high pitch or low, all reach a listener simultaneously.



Sounding the depths

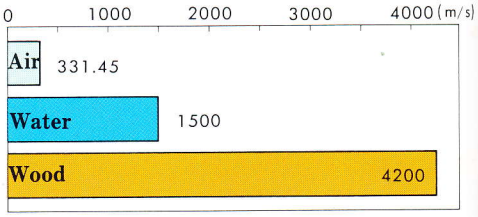
Sonar beams, made up of sound waves, pass easily through ocean water. Sonar relies on the fact that sound waves reflect off the ocean floor; it is used to "sense" the presence of underwater features.



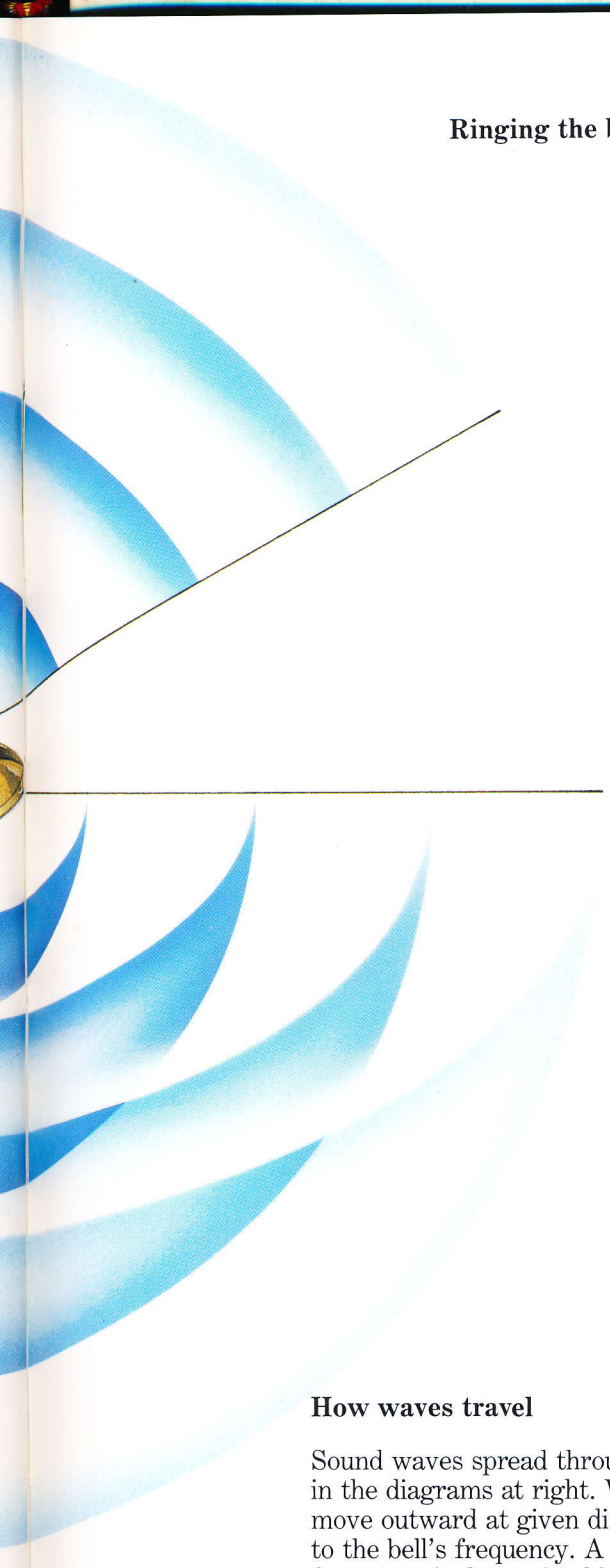
Elastic solids

Sound travels through a sheet of wood. The molecules of most solids are linked in a tight framework that is not easily compressed but hastens the passage of sound waves.

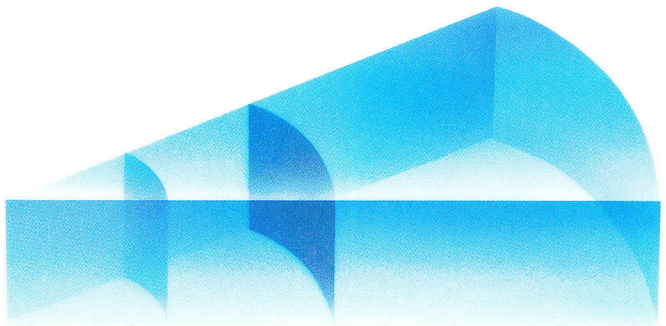
The speed of sound varies depending on the medium it passes through and the medium's temperature. Sound waves travel slowly through a gas because its loose molecular structure is easily compressed. The speed increases in less compressible liquids and becomes even faster in solids, as shown below in metres per second (m/s).



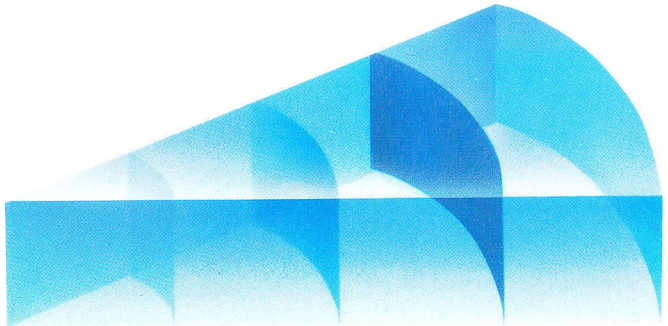
Ringing the bell



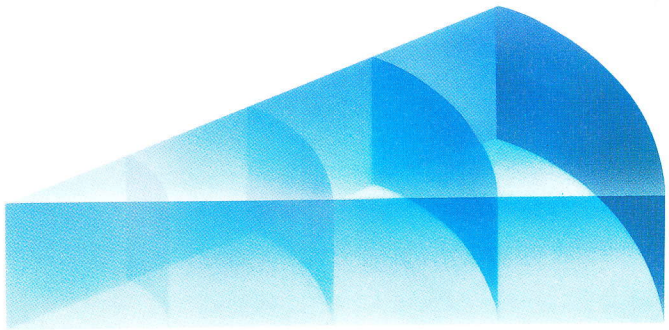
A sonic wave front moves outward from a vibrating bell.



It proceeds at a constant rate through evenly heated air.



A second front follows at a set distance, or wavelength.



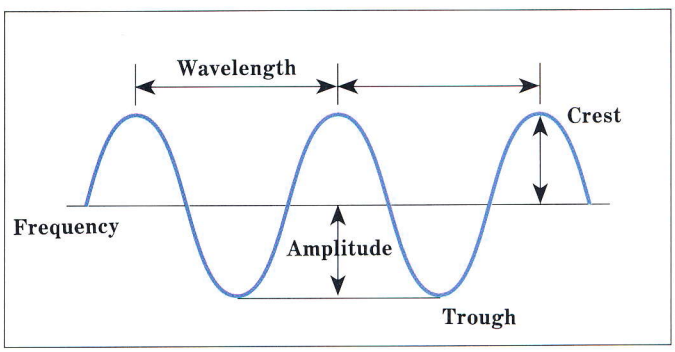
Waves are strongest near the source.

How waves travel

Sound waves spread through the air as in the diagrams at right. Wave fronts move outward at given distances keyed to the bell's frequency. A sound wave's frequency is determined by counting the number of wave fronts passing a given point in a given time.

Portraying an invisible wave

A simple sound wave passing through air is represented graphically as a wavy line (*right*). The crests of the wave represent molecular compression; the troughs indicate the elastic expansion that takes place after the wave front has passed. The more complex a sound, the greater the number of intermediate crests and troughs in the wave-form that portrays it. Loud sounds bearing great energies show high wave heights, or amplitudes.



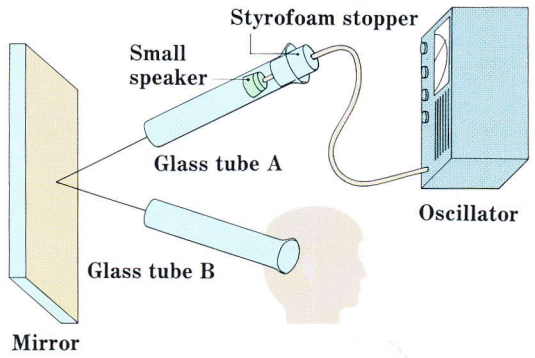
What causes echoes?

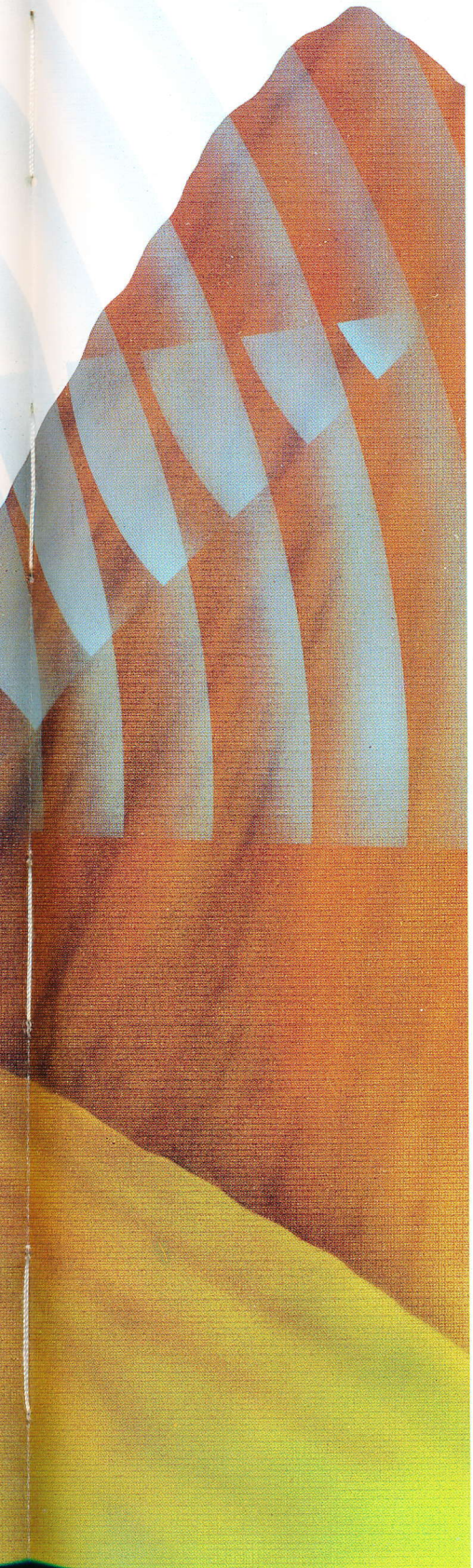
Echoes result when sound waves moving outward from a source—so-called incident waves—run into a solid barrier such as the face of a mountain. Sound waves reflect from, or bounce off, such obstacles at an angle equal to that at which they have struck.

The distance of the barrier from the origin of the sound is a key factor. When the barrier is nearby, the reflected waves make the return trip rapidly enough to mingle with the original waves, and no echo is formed. If the barrier stands at least 15 metres away, the reflected waves will not return until after the incident waves have stopped. Then listeners will hear the sound repeated as if it is coming from the direction of the barrier. Acoustical engineers must plan auditoriums and concert halls with echoes in mind, adding soundproofing and eliminating structural features that might prove overly reflective.

A test of reflection

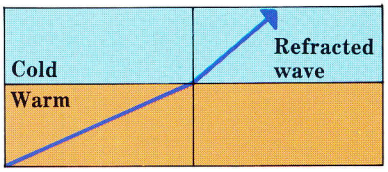
In this experiment, low-frequency waves from an oscillator pass through glass tube A, bounce off a mirror, and enter tube B. The test proves that the angle of the reflected wave matches that of the original one.

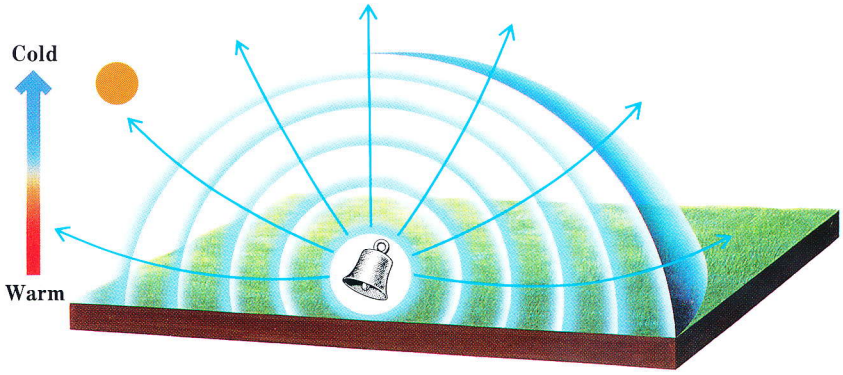




Speedy by day

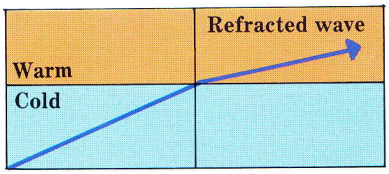
Sound speeds through warm air near the ground (*below*) but slows when reaching cooler upper layers. The change results in upward refraction, or bending, of the wave.

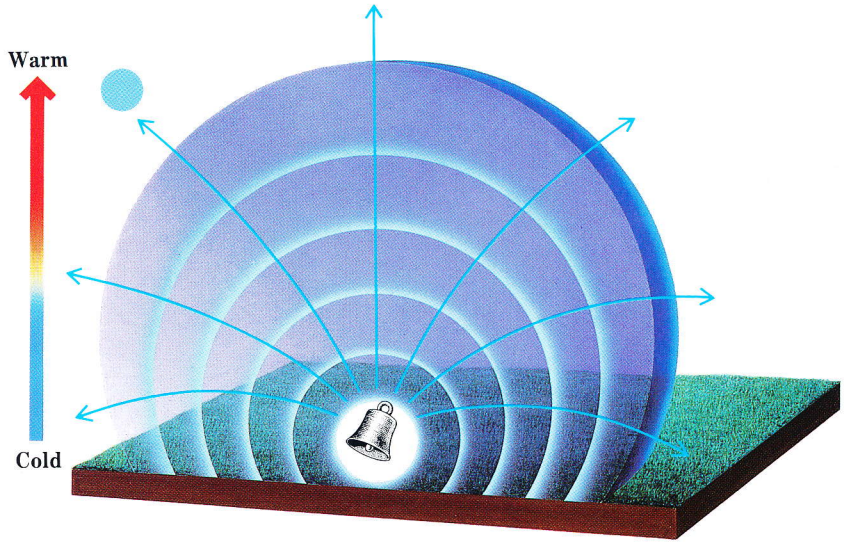




Slow by night

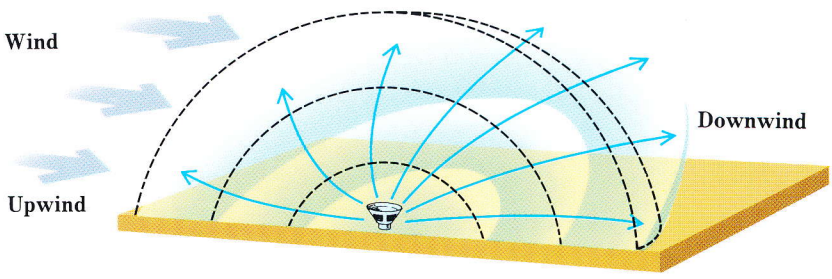
Cool night-time ground temperatures slow the passage of sound (*below*). Warmer overlying layers increase the speed of sound.





Sound travels with the wind

Wind moves more rapidly far above the ground than near the ground. When sound waves spread out from the ground, they travel with the wind. An upwind listener would hear only a faint sound; a downwind listener would hear the bell from far away.



How are tones produced?

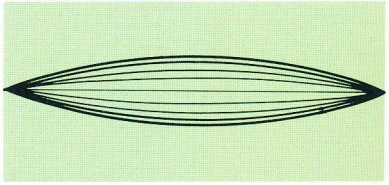
Musicians coax tones, or notes of various pitches, from instruments by controlling their sound-producing vibrations. When a violinist pulls the bow across a string, the string begins to vibrate, or oscillate. Waves travel up and down the string's length, forming patterns called standing waves. Similarly, when the player of a recorder blows into the mouthpiece, standing waves form in the column of air inside the recorder. Each wave produces a different tone. The lowest note a string or an air column can produce is called the fundamental tone. Any time that note is sounded, higher pitches, called overtones, are also produced; this occurs when a fundamental wave breaks up into sections. The distinctive sound, or timbre, of an instrument is caused by the relative strength or weakness of overtones.

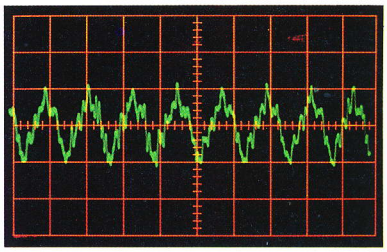
The king of strings

The violin's wooden body is the key to its elegant timbre. When bowed or plucked, the strings vibrate, causing the carved and varnished panels of the instrument to resonate, or vibrate, at the same frequency. This amplifies the sound, so it is loud enough to be heard.

A singing string

A violin string oscillates at a fundamental frequency as shown below. An image of the sound can be viewed on an oscilloscope as a complex wave pattern (*bottom*) typical for stringed instruments.





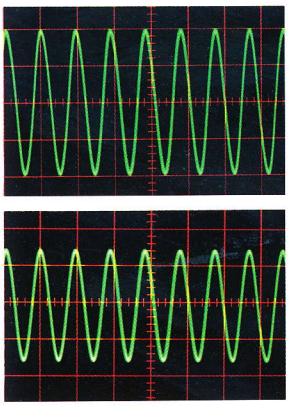
Violin meets recorder

A mellow woodwind

Fluctuating waves of air pulsate through the recorder. These waves form patterns resembling those of a vibrating string.

The structure of waves

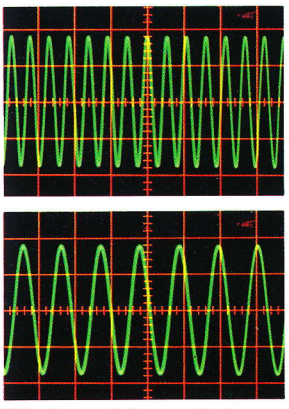
Oscilloscope signals reveal different intensities and pitches. Loud and quiet sounds (*right*) are measured in terms of decibels. People most readily detect waves between 1 and 120 decibels. High and low pitches (*below, right*) are related to frequency, the rate at which crests or troughs of a wave pass a given point.



Loud and soft sounds

A wave machine

An oscilloscope plots the wave-forms of sounds. High-pitch/high-frequency sounds have short wavelengths; low-pitch/low-frequency sounds have long wavelengths.

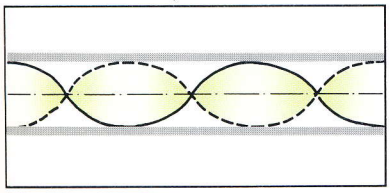


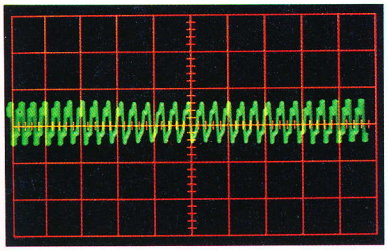
High and low pitches

Sound waves can be viewed on an oscilloscope screen.

The sound of air waves

Overtones appear as divisions in a standing wave in the air column below. At bottom is the relatively simple signature of this sound wave. Woodwinds have a smooth, direct sound.

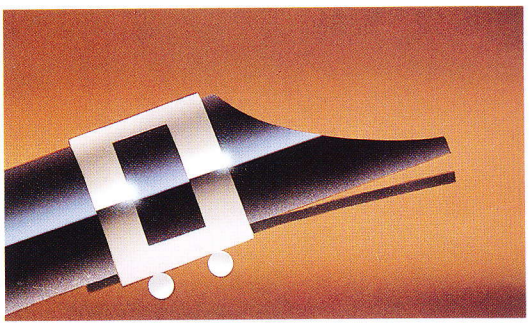




How do wind instruments work?

To produce different notes on a wind instrument such as the clarinet at right, a musician blows into the mouthpiece while depressing leverlike keys to uncover holes along the instrument's body. This action causes shifts in the wavelength of the standing wave that is determined by the length of the air column inside the instrument. It also gives the tone a corresponding drop or rise in pitch. With brass instruments, such as the trumpet and the tuba, the musician changes the mouth position and depresses valves that change the length of the air column.

In the trombone, the air column is adjusted by sliding the curved bottom tube in and out. Holes along the bodies of simple wind instruments, such as the recorder and piccolo, are covered by the fingers to achieve the same effect.



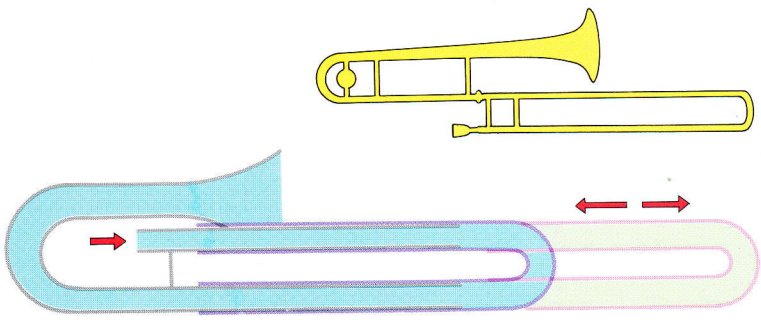
A thin reed in the mouthpiece of a clarinet (*above*) vibrates when a musician blows across it. The vibrations travel down the instrument's tube as compression waves.

One of an ancient breed

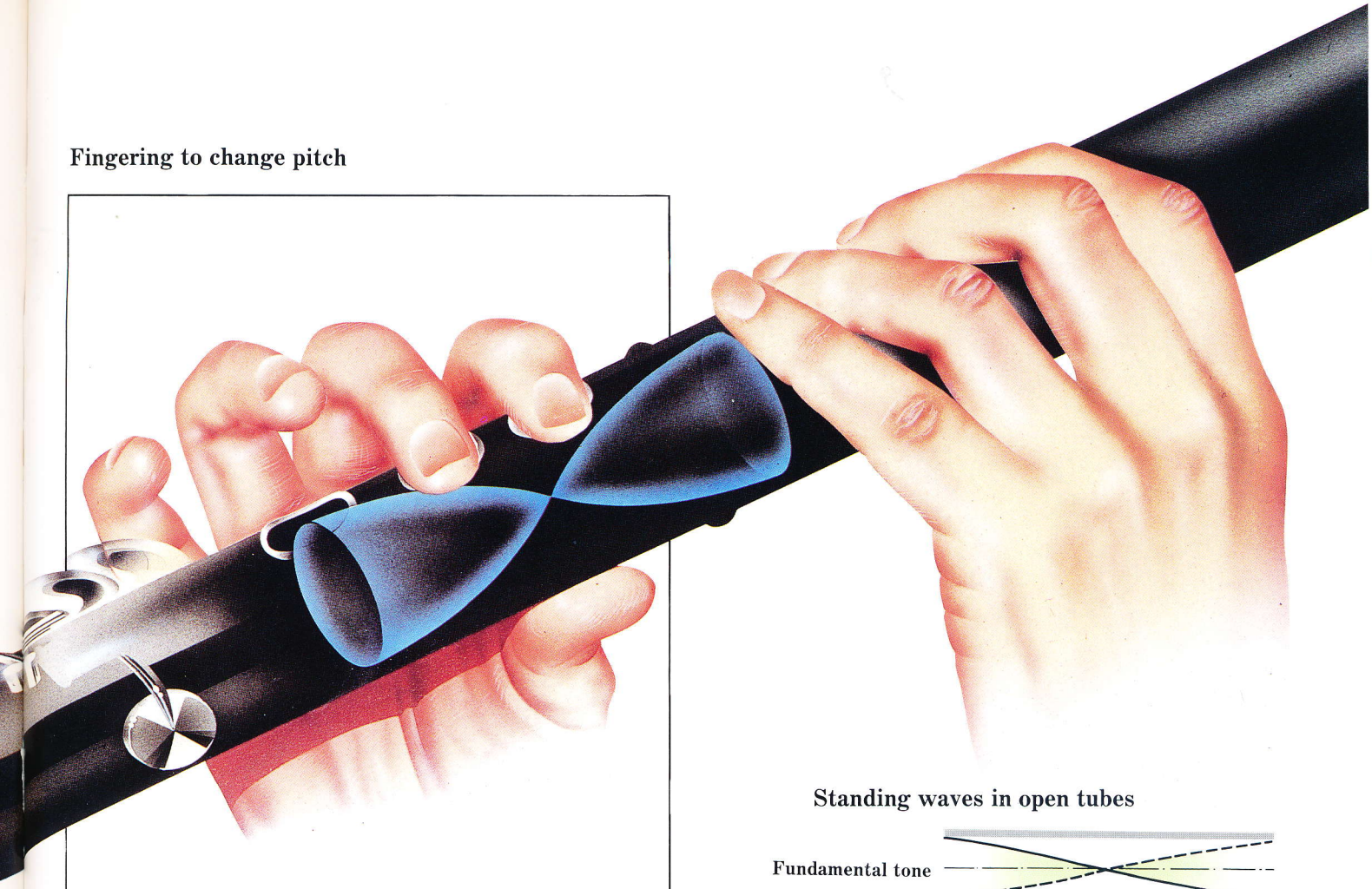
The sophisticated clarinet above is descended from crude bamboo pipes and primitive flutes first crafted by early civilizations. The oldest wind instruments predate stringed ones by several thousand years. The flared open end of the clarinet allows for a dynamic flow of the sound waves into the air.

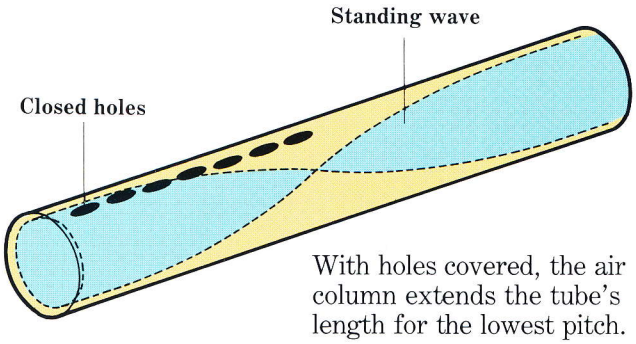
Sliding scales

In the slide trombone, a curved section of brass tubing fits snugly onto the body of the instrument. Moving this section in and out changes the length of the air column and thus the pitch.

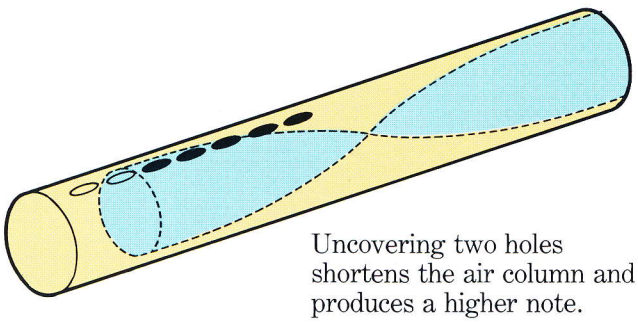


Fingering to change pitch

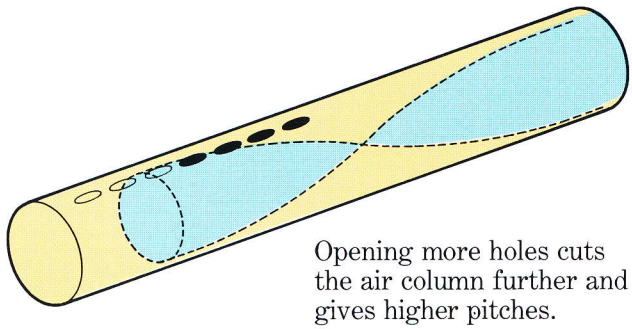




With holes covered, the air column extends the tube's length for the lowest pitch.

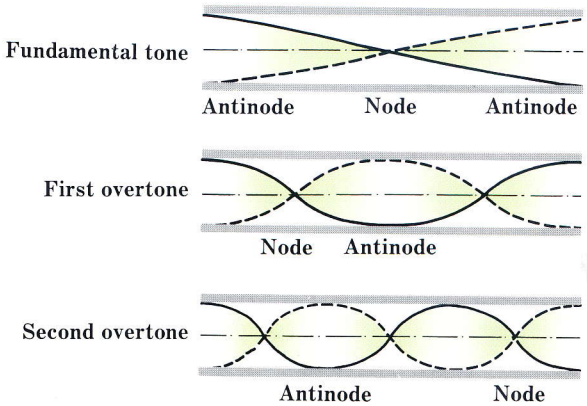


Uncovering two holes shortens the air column and produces a higher note.



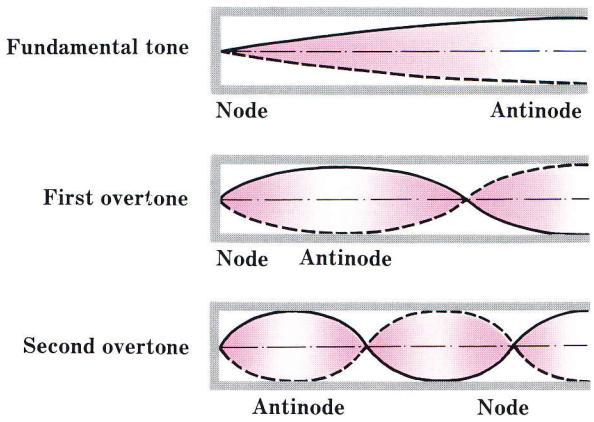
Opening more holes cuts the air column further and gives higher pitches.

Standing waves in open tubes



In a tube that is open at both ends, standing waves form with antinodes, or vibrating segments, at the ends.

Standing waves in closed tubes



In a tube with one closed end, standing waves form with nodes, where no motion occurs, at the closed end and antinodes at the open end.

What is the Doppler effect?

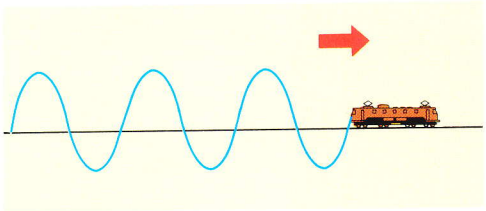
The Doppler effect is the well-known change in sound that occurs when the source of a sound is moving in relation to a listener. To the stationary listener, the sound appears to rise gradually in pitch as the source of the sound approaches, and then to fall as it continues past the listener. This so-called Doppler shift is caused by sound wave fronts that arrive in ever-greater frequency as the moving object nears the listener. The increase in frequency is accompanied by a shrinking of wavelength. As scientists are aware, the higher the frequency of a sound, the higher its pitch. When the object moves away from the listener, the reverse takes place. Frequency drops, wavelength increases, and the apparent tone of the sound that the listener hears becomes lower and lower.

The Doppler effect can be commonly heard in passing train whistles, ambulance or police sirens, and jet plane engines.

An arriving train whistles shrilly.

A receding train

As the train moves away, wave fronts of its whistle take longer to reach a listener, who hears a drop in pitch.

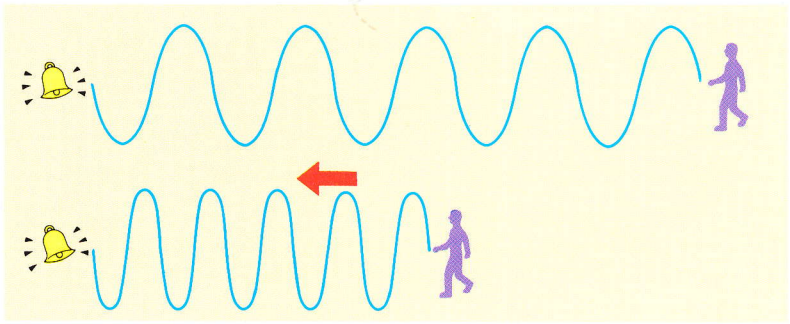


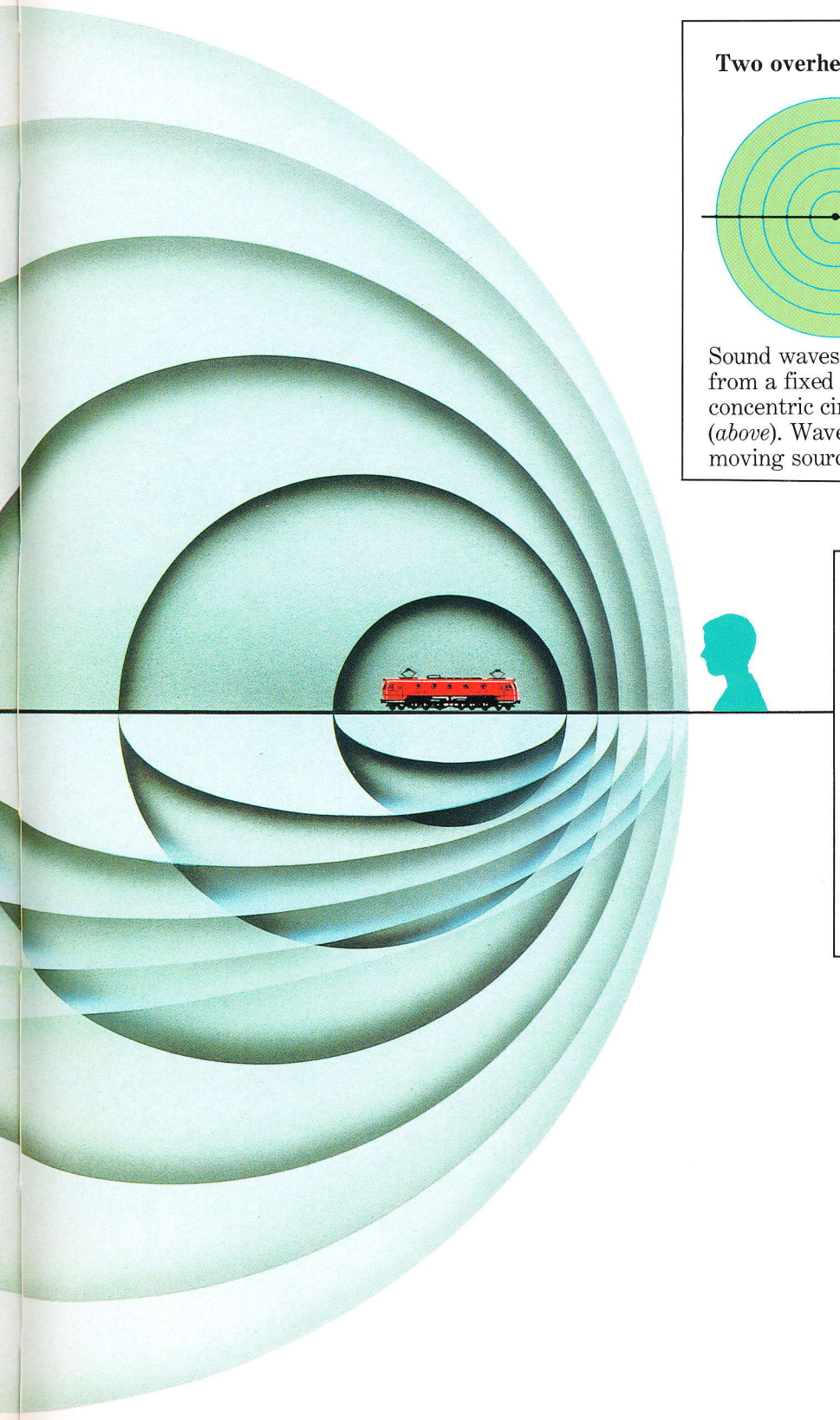
An illusion bred by motion

To a listener on a train, the pitch of its whistle is constant. But to listeners behind or in front of the train (*above, right*), the pitch shifts because of the uneven spacing of wave fronts.

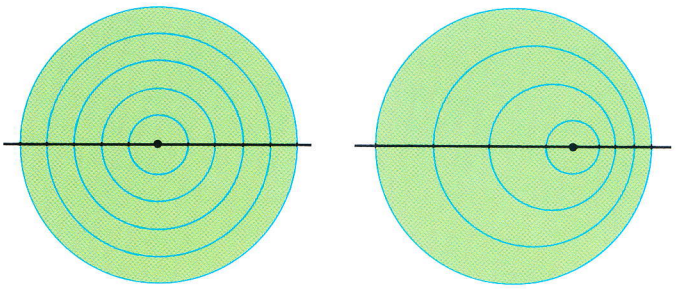
An alternate view

Another way of considering the Doppler effect is to imagine a listener approaching the sound. The closer the walker comes to the bell, the faster the wave fronts reach him, and the higher pitched the tolling of the bell sounds.





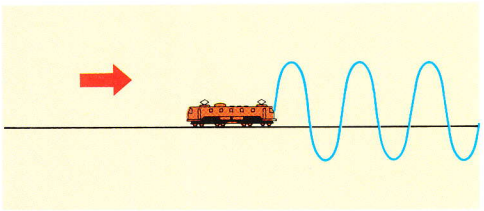
Two overhead views



Sound waves move out from a fixed source in concentric circles (*above*). Waves from a moving source (*above, right*) are pushed ahead of the source. The wavelengths are compressed, and the pitch is raised.

An approaching train

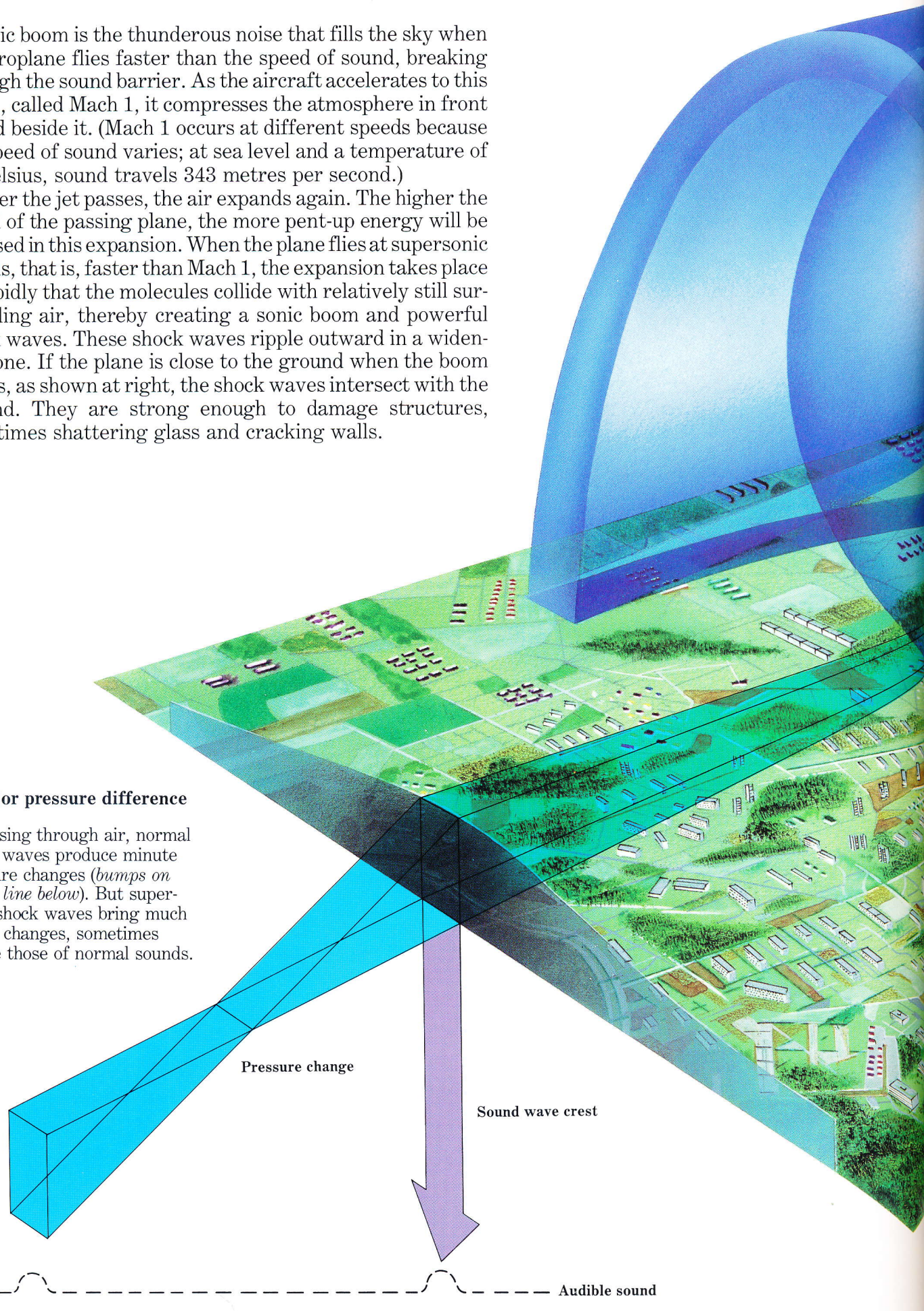
As the train comes closer, sound wave fronts reach a listener ever more quickly and seem to rise in pitch.



What is a sonic boom?

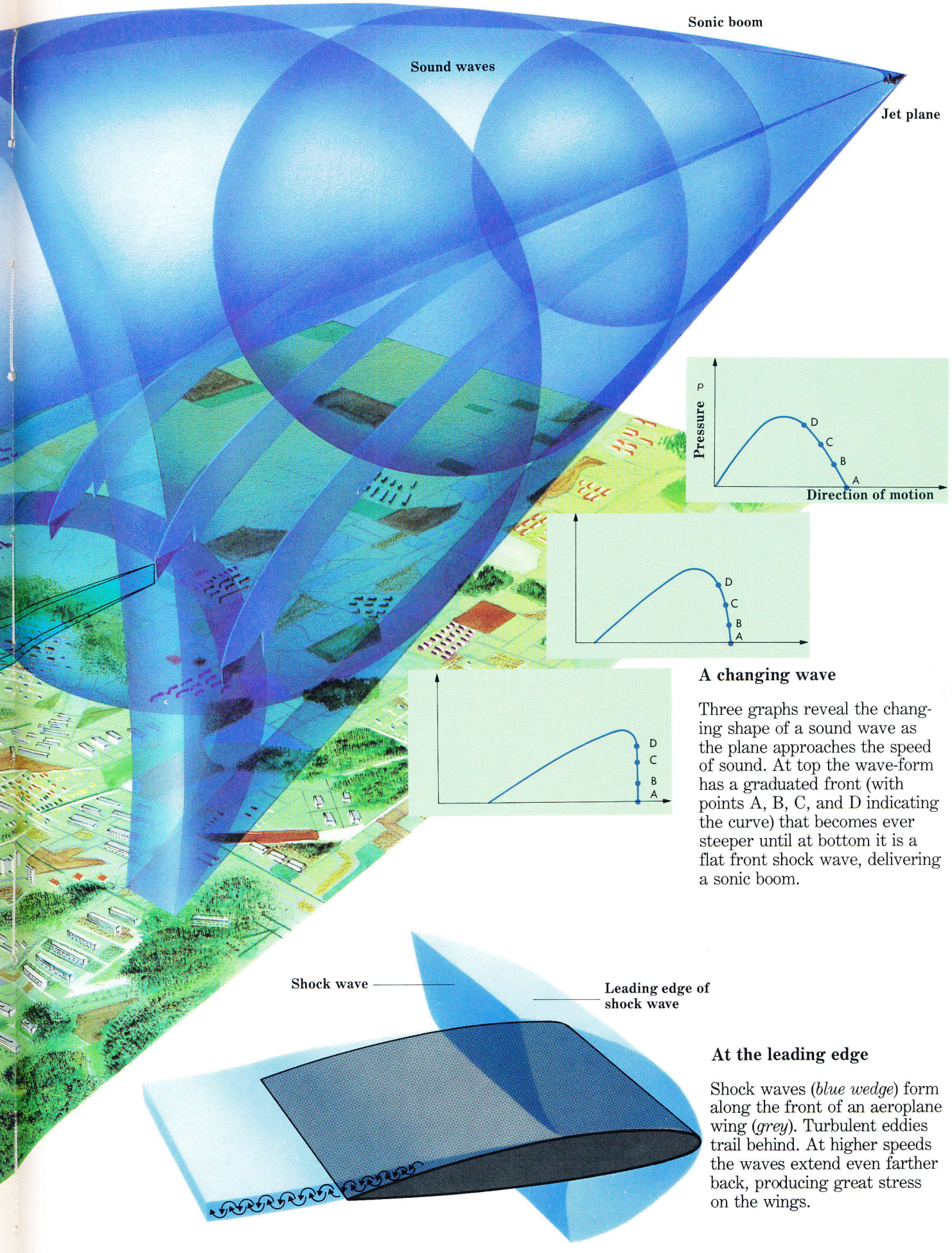
A sonic boom is the thunderous noise that fills the sky when an aeroplane flies faster than the speed of sound, breaking through the sound barrier. As the aircraft accelerates to this speed, called Mach 1, it compresses the atmosphere in front of and beside it. (Mach 1 occurs at different speeds because the speed of sound varies; at sea level and a temperature of 0° Celsius, sound travels 343 metres per second.)

After the jet passes, the air expands again. The higher the speed of the passing plane, the more pent-up energy will be released in this expansion. When the plane flies at supersonic speeds, that is, faster than Mach 1, the expansion takes place so rapidly that the molecules collide with relatively still surrounding air, thereby creating a sonic boom and powerful shock waves. These shock waves ripple outward in a widening cone. If the plane is close to the ground when the boom comes, as shown at right, the shock waves intersect with the ground. They are strong enough to damage structures, sometimes shattering glass and cracking walls.



A major pressure difference

In passing through air, normal sound waves produce minute pressure changes (*bumps on dotted line below*). But supersonic shock waves bring much larger changes, sometimes double those of normal sounds.



A changing wave

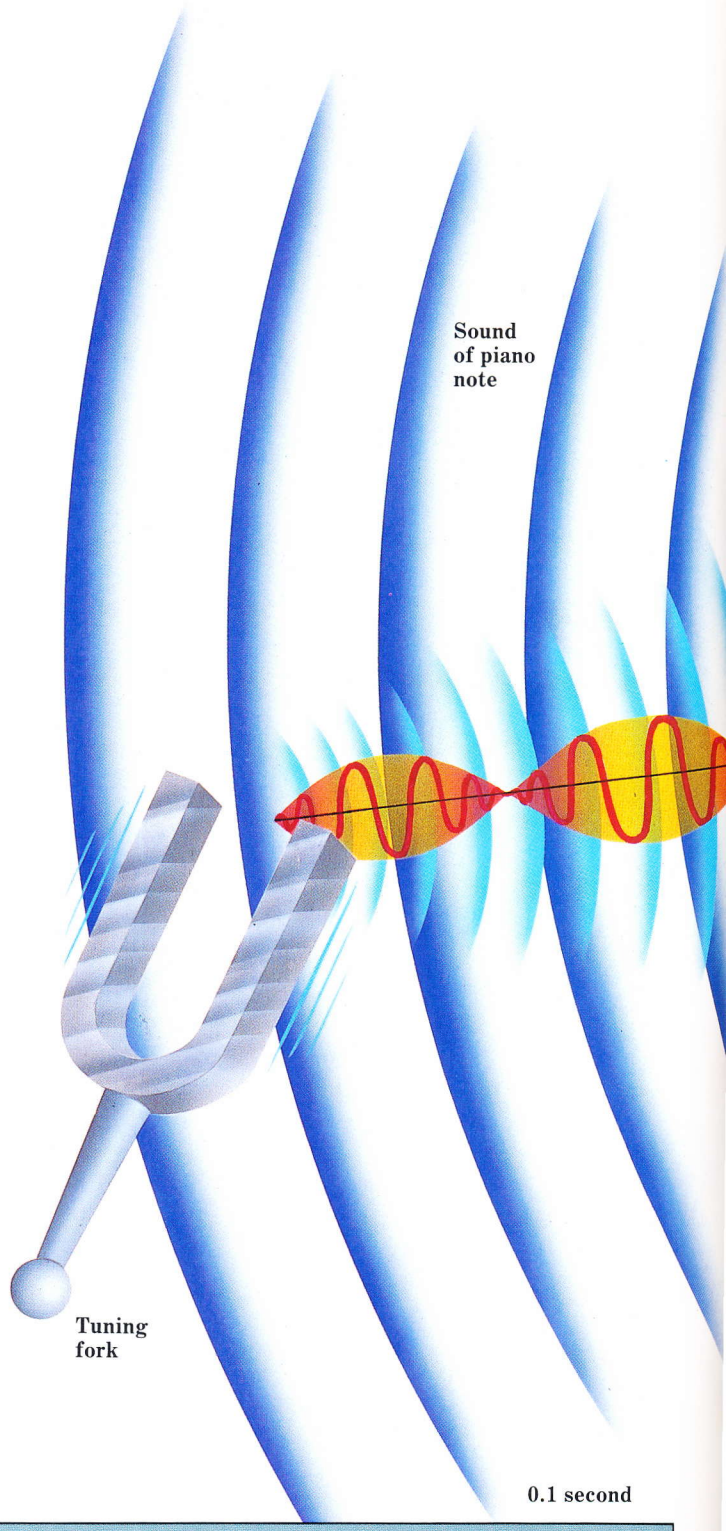
Three graphs reveal the changing shape of a sound wave as the plane approaches the speed of sound. At top the wave-form has a graduated front (with points A, B, C, and D indicating the curve) that becomes ever steeper until at bottom it is a flat front shock wave, delivering a sonic boom.

At the leading edge

Shock waves (*blue wedge*) form along the front of an aeroplane wing (*grey*). Turbulent eddies trail behind. At higher speeds the waves extend even farther back, producing great stress on the wings.

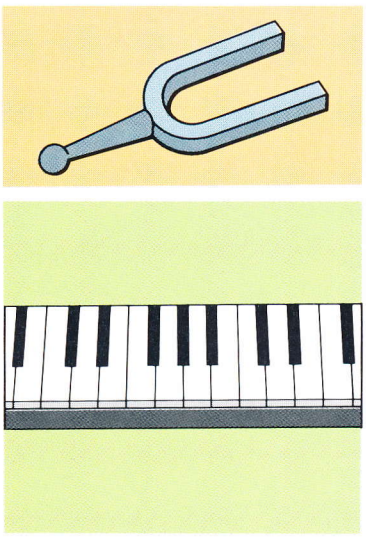
How are musical instruments tuned?

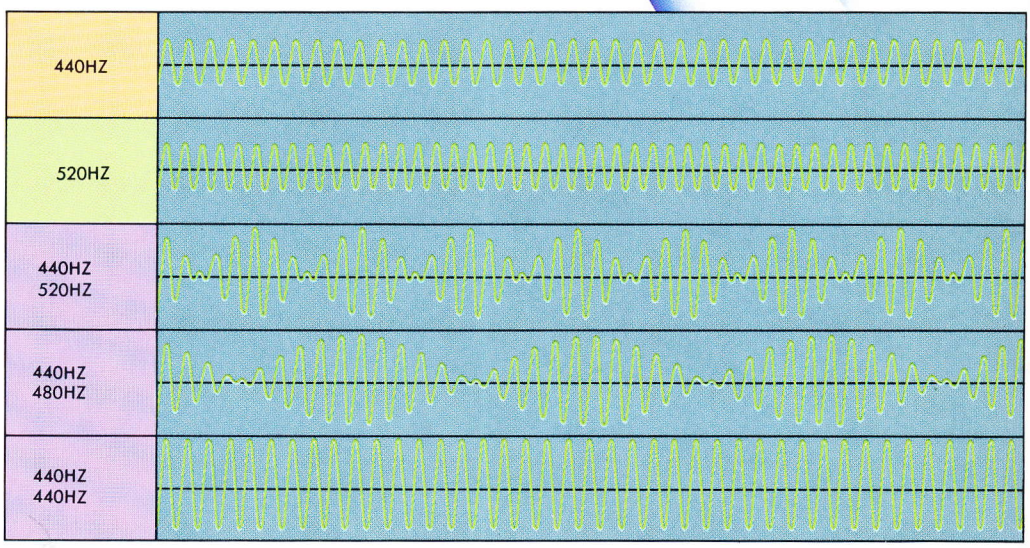
At the beginning of a concert, musicians in a symphony orchestra tune their instruments to a single note played by the oboist. With all the instruments in tune, they can be assured of harmony. But when an instrument such as a piano gets out of tune, a more elaborate procedure is required. Then, a trained technician must tighten or loosen the wires for each key so that its pitch exactly matches that of the appropriate tuning fork. Tuning forks are highly precise tools that yield specific pitches when they are set in vibration. For example, forks designed to vibrate at 262 hertz, or units of frequency, produce the note middle C on the eight-note musical scale, while those at 440 hertz produce the note A in the same octave, called middle A, and those at 524, the note C one octave above middle C. The frequencies of notes an octave apart are related. The higher note vibrates at exactly twice the rate of the lower one. An expert tuner can tell when the piano note precisely matches that of the tuning fork. When the two differ, their sound waves interact in such a way that a pulsing hum, called a beat, is heard. When this humming vanishes, the key is in tune.



Bringing notes into line

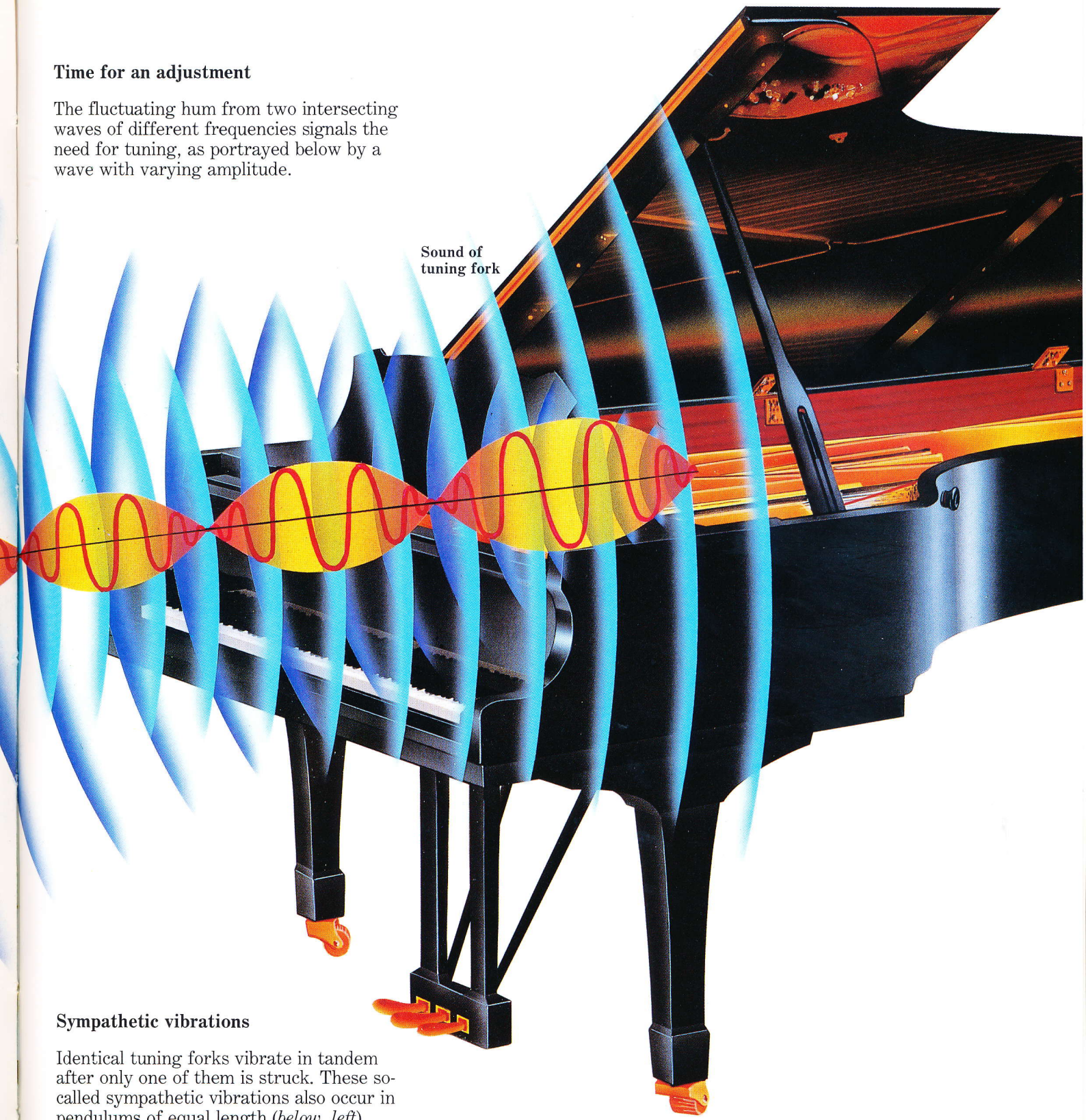
The tuning fork vibrates at 440 hertz, the piano's out-of-tune A key at 520 hertz. When the two interact (*third and fourth bands*), a fluctuating wave results. Once the pitches are the same (*bottom band*), the sound becomes steady.





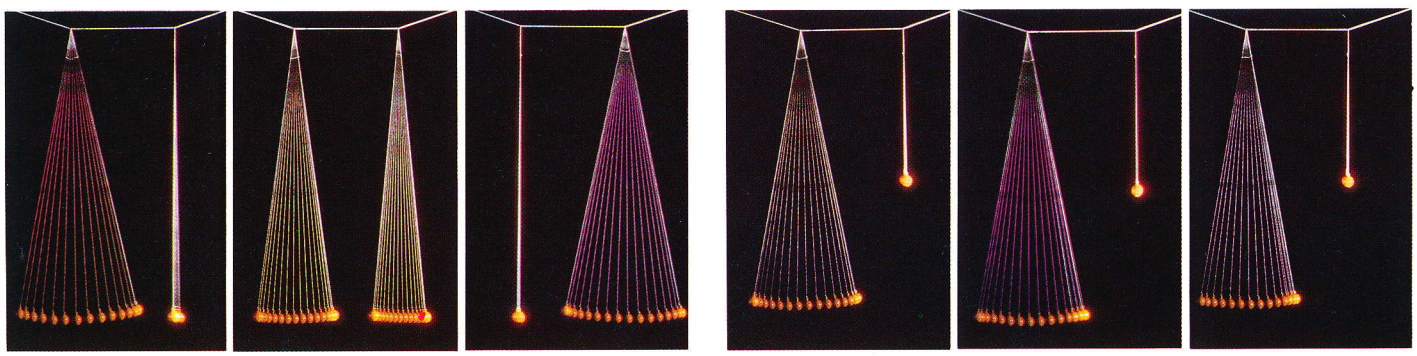
Time for an adjustment

The fluctuating hum from two intersecting waves of different frequencies signals the need for tuning, as portrayed below by a wave with varying amplitude.



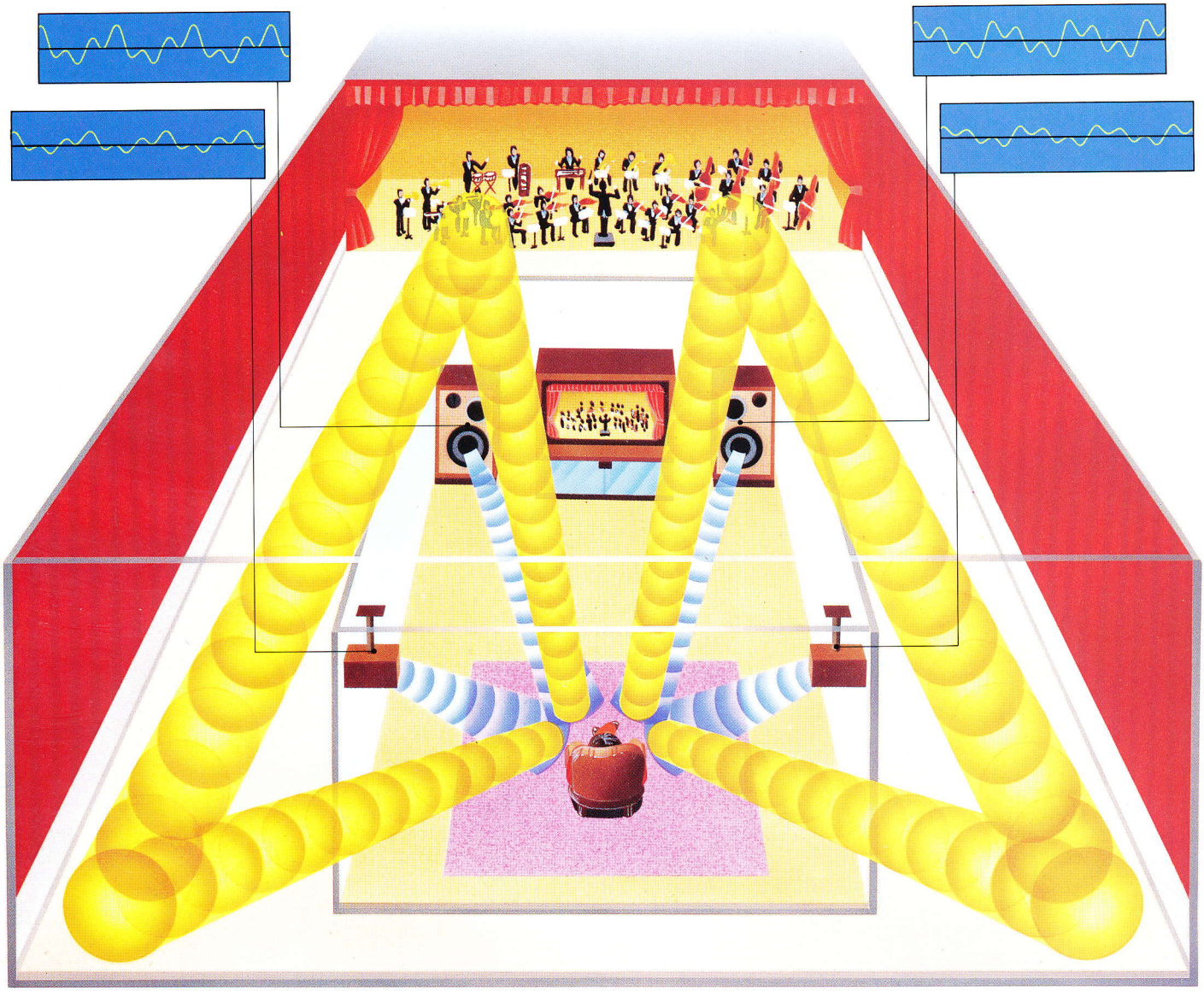
Sympathetic vibrations

Identical tuning forks vibrate in tandem after only one of them is struck. These so-called sympathetic vibrations also occur in pendulums of equal length (*below, left*). Pendulums of unequal lengths (*right*) do not respond.



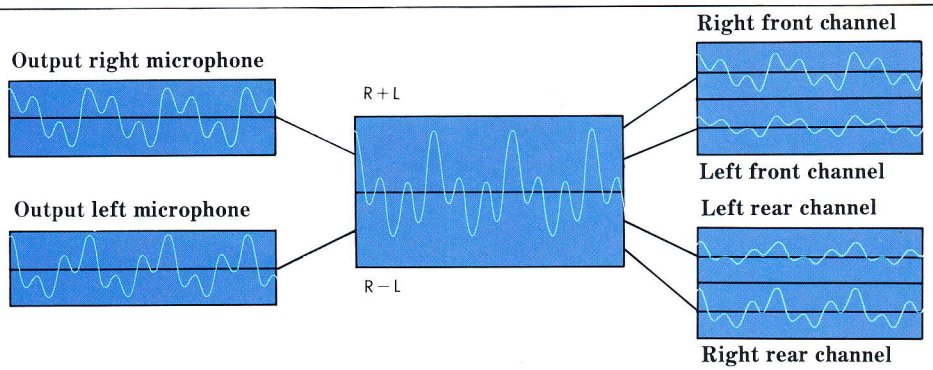
What is a surround-sound system?

A surround-sound system simulates the acoustical experience of being in a concert hall for listeners in a small room. This impression relies on special recordings, which are computer-adjusted to carry separate sound tracks for four channels feeding into left front, left rear, right front, and right rear speakers. Digital processors allow recording engineers to eliminate some sounds and enhance others. This lets engineers take pure sound waves from instruments and combine them with the effects of waves being reflected off and absorbed by the walls of a concert hall. The resulting recording carries enough information to surround a listener with sound.



The surround-sound signal

A surround-sound track consists of two signals: the sum of the output from a pair of microphones, and their difference—sound from one but not the other.



Glossary

Acceleration: The rate at which speed changes, measured in metres per second per second or similar units.
Aerodynamics: The study of the forces that act on objects moving through air.
Aerofoil: Any object, such as an aeroplane wing, designed to generate lift when moving through air.
Alpha particle: A particle consisting of two protons and two neutrons, released by atomic nuclei during radioactive decay.
Alternating current: Electric current that changes direction.
Ammeter: An instrument that measures electric current.
Amplitude: The height of a wave's crests.
Angular momentum: A measure of an object's rotational energy; its value depends on the object's spin rate and mass.
Antinode: A point along a standing wave that has a maximum amplitude.
Archimedes' principle: The principle stating that when an object is partially or fully immersed in a fluid, the upthrust, or buoyant force, on the body is equal to the weight of the volume of water displaced.
Atmospheric pressure: The pressure exerted by the atmosphere; at sea level the normal atmospheric pressure is equal to 1.013×10^5 newtons per square metre. This pressure is defined as one atmosphere, and other pressures are often given in terms of atmospheres. Atmospheric pressure is also defined with reference to the height to which the pressure of the air forces a column of the element mercury in a tube. One atmosphere is equivalent to 760 millimetres of mercury (mmHg).
Barometer: An instrument that measures atmospheric pressure. The two main types of barometer are the mercury-filled and the aneroid, or liquid-free, barometer.
Battery: A cell consisting of a mixture of chemicals that provides an electromotive force when connected to a circuit.
Beta particle: A particle consisting of either an electron or a positron, sometimes released by atomic nuclei undergoing radioactive decay.
Boiling point: The temperature at which a substance changes from liquid to vapour.
Buoyant force: An upward force equal to the weight of a substance, such as air or water, displaced by an object.
Centrifugal force: The "centre-fleeing" force that is experienced as an outward force that balances the inward centripetal force on objects moving in a circle. The force technically does not exist; it represents the effect of inertia.
Centripetal force: The "centre-seeking" force that pulls objects moving in a circle—such as the people in a roller coaster that is running around a circular track—toward the centre.
Circuit: A closed pathway through which electric current flows. Circuits with resistors can be arranged in **parallel**, in which each resistor is attached in a separate loop in the circuit; and in **series,** in which resistors are placed one after another.
Combustion: A rapid chemical reaction of oxygen and another substance, with the production of heat and light; otherwise known as burning.
Concave: Having one or two surfaces that bend inward like the inner surface of a hollow sphere.
Condensation: The process in which vapour changes into a solid or liquid.
Conductor: Material that allows electric current to flow through.
Convection: A process in which heat circulates throughout a volume of liquid or gas.
Convex: Having one or two surfaces that bend outward like the outer surface of a sphere.
Decibel: The standard unit that scientists use to measure the intensity of sound. Normal conversation registers about 60 decibels, while a jet engine's sound can reach 140 to 160 decibels.
Density: The ratio of an object's mass to its volume.
Diffraction: The property of light by which light waves bend around the edges of any object they encounter.
Diode: A device that allows current to flow in only one direction.
Direct current: Electric current that flows in only one direction.
Doppler effect: A phenomenon in which the frequency—and thus pitch—of a sound wave increases for a listener as the source of the sound approaches and decreases as the source recedes.
Drag: The force of friction that retards the movement of an object through air.
Elastic limit: The maximum force from which a stretched or compressed spring will recover its initial shape; any applied force beyond this limit will permanently bend the spring.
Electric current: The flow of electric charge. Electric current is defined as the flow of positive electric charge

from a region of positive potential to one of negative potential. In fact, current is carried in the opposite direction, by negatively charged electrons. The reason is that the direction of current flow was defined before scientists understood that electrons carry current.

Electricity: The field exerted by a charged particle; a stationary particle produces static electricity, and a moving particle produces current.

Electromagnet: A magnet made by wrapping a current-bearing wire around a ferromagnetic material; the current induces a magnetic field in this material.

Electromagnetic induction: The phenomenon in which a changing electromagnetic field induces a current to flow through a nearby conductor.

Electromagnetic radiation: Energy in the form of electromagnetic waves, or photons, that travel at the speed of light; such waves generate both electric and magnetic fields as they propagate. The energy of an electromagnetic wave varies inversely with its wavelength. **Gamma rays** have the highest energy and shortest wavelength, followed in order of descending energy and increasing wavelength by **x-rays, ultraviolet radiation, visible light, infrared radiation,** and **radio waves.**

Electromotive force (voltage): The force exerted in accelerating electrons along a circuit to form a current.

Electrons: One of the three components—with protons and neutrons—of atoms. Electrons have a negative electric charge and orbit the atom's nucleus.

Energy level: Any orbit in which the electrons surrounding an atomic nucleus may reside.

Evaporation: The process by which a liquid slowly vaporizes.

Ferromagnetic material: Any material, such as iron, that can be magnetized.

Filament: The thin thread in incandescent lights that glows when heated by electric current.

Fizeau's experiment: An experiment to determine the speed of light devised in 1849 by French physicist Armand Fizeau. By measuring the speed at which a cogwheel blocked light beams, Fizeau estimated the speed of light at 312,864 kilometres per second. The accepted value today is 299,792.458 kilometres per second.

Fluorescent light: Light generated when an electric current excites gaseous mercury atoms; these atoms then emit ultraviolet radiation that causes a chemical called a phosphor to glow.

Focal length: The distance from the focal point to the centre of a lens or mirror.

Focal point: The spot at which all light waves meet as they either reflect off a mirror or pass through a lens.

Force: The effect that causes objects to move when it acts on them. Four forces exist in nature: gravity, electromagnetism, and the strong and weak nuclear forces.

Fossil fuel: Any substance, such as oil, coal, or natural gas, generated by the decay of organic matter millions of years ago.

Foucault's experiment: A measurement of the speed of light in 1850 by French physicist Jean Foucault, based on the original experiment of Armand Fizeau. Foucault obtained a value of 297,870 kilometres per second for light speed—close to the accepted modern value of 299,792.458 kilometres per second.

Frequency: The number of wave crests in a moving wave that pass a given point per second.

Friction: A force that prevents motion between objects.

Fundamental tone: The sound produced by the longest possible wavelength of a standing wave; in musical instruments, the fundamental tone is the lowest-frequency sound generated.

Galileo's experiment: A fundamental observation of balls rolled along inclined planes that permitted Italian physicist Galileo Galilei to describe the nature of inertia correctly.

Gear ratio: The ratio of gear sizes or number of teeth for two gears either in contact with one another or connected by a chain.

Geiger counter: A device that measures radioactivity by counting the number of charged decay products that strike it.

Generator: Any machine that converts mechanical motion into electric current.

Geothermal power: The use of steam produced naturally in deep underground wells to run a turbine and generate electricity.

Gravitational field: The space through which a body's gravitational force can be felt.

Gravity: The force responsible for the mutual attraction of separate masses. The gravitational force between two objects is proportional to their mass and the distance between them.

Ground state: The lowest energy level of an electron.

Heat energy: A measure of the total of the energies contained in all the molecules of an object.

Heat of transformation: The energy necessary to induce

a phase change in a substance.

Hertz: A fundamental measure of the frequency of waves. A single hertz is one cycle per second.

Hologram: A photograph that creates a three-dimensional image when a powerful beam of light is shone on it. Creating and viewing holograms was made possible by the invention of the laser.

Hydroelectric power: The production of electricity using the force of water falling from a height. The falling water turns huge turbine blades, which in turn create the power to turn a magnet inside an AC generator.

Incandescent light: Light generated by the electrical heating of a thin filament; as the filament heats up, it gives off light.

Inclined plane: One of the five types of simple machines that reduce the amount of effort needed to raise an object. The typical inclined plane consists of a tilted ramp up which a heavy object can be moved. The tilt makes such movement easier by dividing the object's weight into two components.

Inertia: The tendency of a moving body to remain moving and of a stationary body to remain motionless.

Insulator: A poor conductor of heat or electricity.

Interference: The property of light by which light waves strengthen or cancel each other when they meet.

Kelvin scale: A scale of temperature that defines as zero the lowest temperature that can possibly be reached. Each Kelvin degree is the same magnitude as a Celsius degree. The freezing point of water is 273.16° on the Kelvin scale.

Kinetic energy: A measure of an object's energy of motion; the faster an object moves, the greater is its kinetic energy.

Laser: A device that produces a very strong beam of light that has only one wavelength.

Lever: One of the five types of simple machines, this is a narrow beam that rotates around a single point, called the **fulcrum**. By using levers, people can move objects far more easily than if they try to move them by hand. Engineers divide levers into three types: first-, second-, and third-class.

Lift: The force that propels the wings of aeroplanes, hang-gliders, and other flying objects upward. It is caused by the presence of a zone of high pressure below a wing and a zone of low pressure above it.

Light: Electromagnetic radiation with wavelengths between about 0.00004 centimetres and 0.00008 centimetres; such wavelengths are perceived by the human eye as colours.

Magnetic field: The area throughout which the attractive or repellent force of a magnet can be felt.

Magnetic poles: The ends of a magnet, called north and south, where a magnetic field respectively emanates or converges.

Magnetism: The force of attraction or repulsion between two objects that have molecules arranged in such a way that they generate a magnetic field.

Magnus effect: A force on a spinning object, such as a baseball, that is proportional to the spin rate, drag, and speed of the ball.

Mass: A measure of the total amount of material in an object, determined by its tendency to resist acceleration.

Mechanical advantage: The degree to which a simple machine changes the effort necessary to do a job.

Michelson-Morley experiment: An experiment performed in 1887 by two American physicists which proved that the speed of light is constant for every observer.

Neutrino: A subatomic particle that possesses no electric charge and little or no mass.

Neutrons: One of the three constituent parts—with protons and electrons—of an atom; the neutron resides in the atom's nucleus and possesses no electric charge.

Node: A point along a standing wave that has zero amplitude.

N-type silicon: Silicon that has an excess of negative charge.

Nuclear energy: A method of generating electricity in which the heat from radioactive decay is used to boil water; the resulting steam is used to spin a turbine.

Nucleus: The centre of an atom around which the electrons orbit; it consists of the atom's protons and neutrons.

Objective lens: The lens on some types of telescopes that forms the image seen by the viewer.

Object wave: A beam of laser light used in making holograms that reflects off the object being photographed onto a piece of film.

Ocean thermal power: A method of generating electricity in which surface water evaporates a liquid with a low boiling point; the resulting vapour is used to spin a turbine.

Ocular lens: A lens that acts as the eyepiece.

Optical pyrometer: An instrument that measures temperatures up to 3,000° Celsius. It works by matching

the brightness of a hot object to that of a tungsten light-bulb filament of known temperature.

Orbit: The path of a heavenly body moving about another under gravitational attraction. The term is also applied to the movement of electrons around atomic nuclei.

Oscilloscope: A machine that turns sound waves into electronic signals and displays the signals on a screen for analysis.

Overtone: The sound produced by a standing wave that has a wavelength equal to a specific fraction of its fundamental tone.

Oxidant: The portion of rocket fuel that provides oxygen, necessary for burning the fuel.

Phase change: A change in the state of matter caused by the addition or removal of heat. Typical phase changes are the boiling and freezing of water.

Phosphor: A chemical substance that emits light when excited by radiation.

Pitch: A property of sound that is related to the frequency of a sound wave. High-frequency waves produce high pitch and low frequencies low pitch.

Positron: A subatomic particle that has the same mass as an electron but possesses a positive charge.

Potential energy: The amount of energy that an object possesses as a result of its position. If an object is moved upward against the force of gravity, its potential energy increases.

Precession: A wobble in the motion of a spinning object, such as a top or a planet, caused by the action of torque on the object's spin axis.

Pressure: Force applied against a surface. Pressure is measured according to its strength across a given area.

Prism: A device that separates white light into its component colours—red, orange, yellow, green, blue, indigo, and violet.

Propagation: The property of light by which it travels in straight lines.

Propellant: A substance that provides thrust when burnt, such as the fuel used in rockets.

Protons: One of the three constituents—with neutrons and electrons—of atoms; protons reside in the atom's nucleus and possess a positive charge.

P-type silicon: Silicon that carries a positive electric charge.

Pulley: One of the five types of simple machines, this is a chain or belt passed around a wheel or series of wheels. It reduces the amount of effort needed to raise an object.

Radioactivity: The energy released when an atomic nucleus breaks up.

Real image: The image formed by a lens or mirror where light rays cross.

Reference wave: A beam of light used in making holograms that strikes the same piece of film as the object wave but does not reflect off the object being photographed.

Reflection: The property of light or sound by which it bounces off surfaces.

Refraction: The property of light or sound by which it changes direction when passing from one medium to another.

Resistor: Any object that resists the passage of an electric current.

Rømer's estimate: The first rough estimate of the speed of light, made in 1676 by Danish astronomer Ole Rømer. Based on slight discrepancies in the duration of eclipses of the moons of Jupiter, Rømer concluded that light travels at 219,904 kilometres per second. The modern value for the speed of light is 299,792.458 kilometres per second.

Scintillation counter: A device that produces an electric signal whenever a charged particle hits it.

Screw: One of the five types of simple machines, this is an inclined plane wrapped around a cylinder. Screws convert rotary motion into straight-line pressure; a typical example is a car jack, which uses rotational motion to lift a car directly upward.

Semiconductor: Any material, such as silicon, that can either conduct or block the flow of electricity.

Simple machine: A simple mechanical device that can redirect a force, turn a small force into a larger one, or magnify the distance over which a force acts. Scientists define five types of simple machines: the lever, the wheel and axle, the pulley, the inclined plane, and the screw.

Solar power: The process of generating electricity from the sun. Heat from the sun can be used to turn water into steam to drive a turbine, or sunlight can be used to power a solar cell.

Solenoid: A coil of wire wrapped around a ferromagnetic material to produce an electromagnet.

Sonic boom: A loud noise produced by the rapid expansion of air molecules when an object exceeds the speed of sound.

Sound wave: A mechanical wave formed from the alternating compression and expansion of the substance

through which the wave travels.

Speed of light: One of the fundamental constants of physics. In a vacuum, light travels at 299,792.458 metres per second.

Spring: A mechanical device that stretches and compresses according to a simple law. Springs play an important role in scales and balances.

Static electricity: A build-up on an object of either negative charge, from the gain of electrons, or positive charge, from the loss of electrons.

Superconductivity: A phenomenon in which some materials, when cooled to an extremely low temperature, conduct electricity without resistance.

Sympathetic vibration: A phenomenon in which the sound waves generated by a vibrating object, such as a tuning fork, induce a nearby identical object to vibrate.

Temperature: An indirect measurement of the average speed of vibration of the molecules of a substance.

Thermal conductivity: A measure of how well or poorly a material permits the passage of heat.

Thermal energy: The amount of internal energy contained by a substance; it is the sum of the kinetic energies of all the molecules in the substance, determined by the substance's temperature.

Thermoelectric power: A method of generating electricity in which the heat from the burning of fossil fuels turns water into steam; the steam then turns the blades of a turbine.

Thermogram: A type of thermometer used to measure excessively high temperatures. It works by detecting infrared radiation from hot objects.

Thrust: Reaction force on a rocket as a result of the expulsion of high-speed exhaust gas.

Tidal power: The generation of energy based on the ebb and flow of ocean tides.

Timbre: The distinctive sound produced by a particular musical instrument; it is the product of the instrument's range of tones and the materials used in its construction.

Torque: Any force that acts to turn an object.

Transformer: A device that transfers electrical energy from one AC circuit to another.

Transistor: A semiconductor that can be used as a switch in electronic circuits.

Transition point: The temperature at which a conductor of electricity loses all resistance and becomes a superconductor.

Transverse wave: A wave in which the motion of the medium is perpendicular to the motion of the wave front.

Uranium-235: The substance that, when split under controlled conditions, produces nuclear power.

Vaporization: The process in which a solid or liquid changes phase into a gas.

Vapour pressure: The pressure exerted near the surface of a liquid by evaporated molecules of the liquid.

Vector: Any quantity that indicates magnitude and direction.

Virtual image: An image formed by a lens or a mirror that makes rays of light spread out from a common apparent source.

Viscosity: The tendency of a liquid to resist flowing because of friction between the liquid's molecules.

Voltage: The force exerted in accelerating electrons along a circuit to form a current.

Voltage drop: The decrease in the voltage of a circuit that occurs when current passes through a resistor.

Voltmeter: A device that measures electrical voltage.

Volume: The amount of space taken up by a substance.

Wave front: The moving crest of a wave.

Wave power: The generation of energy based on the ebb and flow of ocean waves.

Wavelength: The distance between the crests of a wave.

Weight: A measure of the force of gravity acting on an object. The stronger the gravitational field in which an object is, the greater the object's weight will be.

Wheel and axle: One of the five types of simple machines, this reduces the amount of effort needed to move an object. The most common example of this machine is the pedal and sprocket of a bicycle. By exerting an effort on the rotating pedals, a cyclist propels the bicycle forward at a faster speed than a person could achieve on foot.

Windmill: A device that generates electricity inexpensively, reliably, and in a nonpolluting way by capturing the power of the wind. A basic windmill consists of one or more blades, a mechanism to keep the blades rotating at a constant speed in the face of changing winds, and a generator.

Work: A measure of the amount of energy exerted by a force. It is the product of a force and the distance over which it operates.

As used in this volume, 1 billion = 1,000,000,000.