DK Eyewitness

# MATTER

# Eyewitness
# Matter


Open and shut mold for making apothecaries' vials (19th century)

Metals produced by electrolysis (mid 19th century)

Crookes's thallium compounds and notebook (1860s)

Measuring cylinder (19th century)

Model of adenovirus (20th century)

Ammonium dichromate crystals

Bunsen burner (19th century)

Graphite

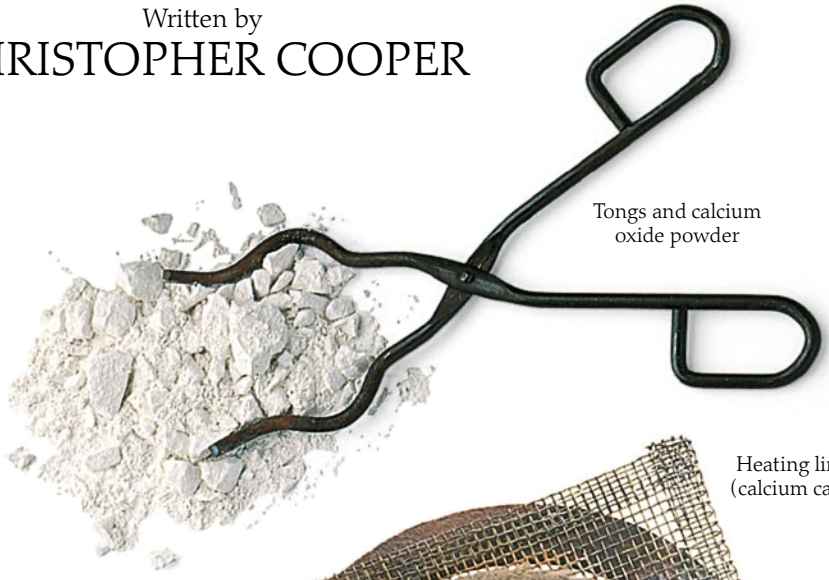
Roman coins
(2nd century)

Boxes of chemicals
(19th century)

# Eyewitness Matter

Written by
CHRISTOPHER COOPER

Tyndall's boiling point apparatus
(1880s)



Tongs and calcium oxide powder

Heating limestone
(calcium carbonate)

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Boxes of chemicals (19th century)



Thermometer of Lyons (18th century)

Ancient Egyptian mirror




Items from a box of flame test equipment (19th century)

Bunsen burner (1872)

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**Project editor** Sharon Lucas
**Designer** Heather McCarry
**DTP manager** Joanna Figg-Latham
**Production** Eunice Paterson
**Managing editor** Josephine Buchanan
**Senior art editor** Neville Graham
**Special photography** Dave King
**Editorial consultant** Alan Morton, Science Museum, London
**Special consultant** Jack Challoner
**US editor** Charles A. Wills
**US consultant** Harvey B. Loomis

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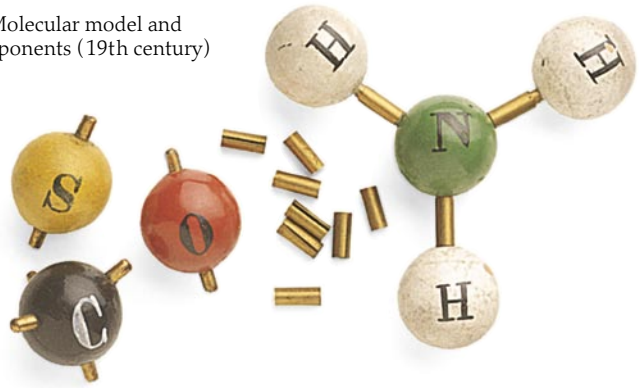

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# What is matter?

EVERYTHING FOUND EVERYWHERE in the universe – from the farthest star to the smallest speck of dust – is made of matter in an incredible variety of forms. About 200 years ago heat was regarded by many scientists as being a special sort of matter. But now it is known that heat is simply the motion of tiny particles of matter (pp. 38-39). Sound, too, is a certain type of movement of matter. Forms of energy such as radiation (for example, light, radio waves, and X-rays) are generally regarded as not being matter, though they are very closely linked to it. All the different kinds of matter have one thing in common – mass. This is the amount of material in any object, and shows itself as resistance to being moved. A truck, for example, has more mass and is much harder to move than a toy car. Every piece of matter in the universe attracts every other piece of matter. The amount of matter is important – a large piece attracts other matter more strongly than a small piece.

**A CONTAINED UNIVERSE**
This terrarium is a microcosm of the living world. It contains the three states of matter – solids (pp. 12-13), liquids (pp. 18-19), and gases (pp. 20-21), as well as interesting substances found in the world of matter.

**THE LIVING WORLD**
All living matter (pp. 42-43) can organize itself into intricate forms and behave in complicated ways. It was once thought that matter in living things was controlled by a "vital principle," a sort of ghostly force. But now scientists think that living and nonliving matter obey the same laws.

*Plants grow upward to reach the light*

**MIXING AND SEPARATING MATTER**
Gravel, sand, and water can be made into a mixture (pp. 26-27), and can easily be separated afterwards. Each of these materials is made of other substances that are more strongly combined and very hard to separate. Water, for example, is a combination of the gases hydrogen and oxygen. Such a close combination is called a chemical compound (pp. 26-27).

*A mixture of gravel, sand, and water*

**METALLIC MATTER**
Metals (pp. 16-17) are found in rocks called ores. Pure metals are rare, and usually they have to be separated from their ores. Once separated, they are often combined with other materials to form alloys – mixtures of metals and other substances.

*Lead is a metal which looks solid, but flows extremely slowly over decades*

**SOLUTIONS AND COLLOIDS**
Substances can often dissolve in a liquid or solid. They form solutions – they are mixed very thoroughly with the liquid or solid, breaking up into groups of a few atoms, or even into single atoms (these are the smallest normally existing particles of matter, pp. 34-35). A colloid (pp. 24-25) consists of larger particles of matter that are suspended in a solid, liquid, or gas.

*Glass is transparent matter*

**THE WORLD OF GASES**
When the particles of a substance become separated from each other, the substance becomes a gas. It has no shape of its own, but expands to fill any space available. Air (largely a mixture of nitrogen and oxygen) was the first gas to be recognized. It was many centuries before scientists realized that there are other gases as well as air. This was because gases tend to look similar – they are mostly colorless and transparent.

*Condensation is caused by molecules of water vapor cooling and turning into a liquid*

*This butterfly is made of some of the millions of varieties of living matter on earth*

**LIQUID MATTER**
Liquids, like gases, consist of matter that can flow, but unlike gases, they settle at the bottom of any container. Nearly all substances are liquids at certain temperatures. The most important liquid for living creatures is water. Most of the human body is made up of water. It forms the bulk of human blood, which transports dissolved foodstuffs and waste products around the body.

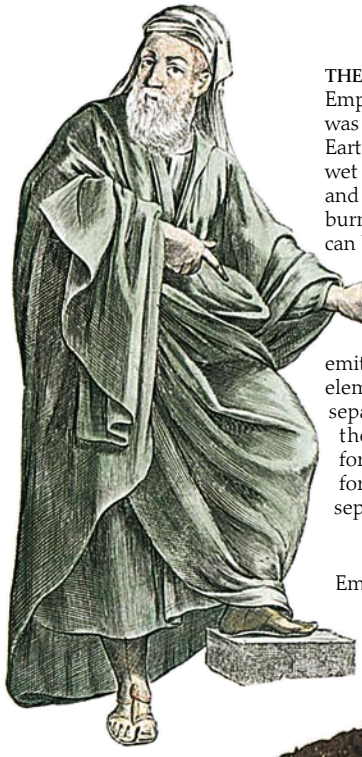
*Water contains dissolved oxygen and carbon dioxide gases from the air*

**SOLID SHAPES**
The metal and glass (pp. 24-25) of this terrarium could not act as a container for plant and animal specimens if they did not keep a constant shape. Matter that keeps a definite shape is called solid. However, most solids will lose their shape if they are heated sufficiently, turning into a liquid or a gas.

*Solids such as rock keep a definite shape*

# Ideas of the Greeks

ANCIENT GREEK PHILOSOPHERS vigorously debated the nature of matter and concluded that behind its apparent complexity the world was really very simple. Thales (about 600 BC) suggested that all matter was made of water. Empedocles (5th century BC) believed that all matter consisted of four basic substances, or elements – earth, water, air, and fire – mixed in various proportions. In the next century Aristotle thought there might be a fifth element – the ether. Leucippus (5th century BC) had another theory that there was just one kind of matter. He thought that if matter was repeatedly cut up, the end result would be an uncuttable piece of matter. His follower Democritus (about 400 BC) called these indivisible pieces of matter "atoms" (pp. 34-35), meaning "uncuttable." But Aristotle, who did not believe in atoms, was the most influential philosopher for the next 2,000 years, and his ideas about elements prevailed.



Empedocles

**THE FOUR ELEMENTS IN A LOG**
Empedocles's idea of the four elements was linked to certain properties. Earth was dry and cold, water was wet and cold, fire was hot and dry, and air was hot and wet. In the burning log below, all four elements can be seen. Empedocles thought that when one substance changes into another – such as when a burning log gives off smoke, emits sap, and produces ash – the elements that make up the log are separating or recombining under the influence of two forces. These forces were love (the combining force), and hate or discord (the separating force).

*Design on the coin has been smoothed away*

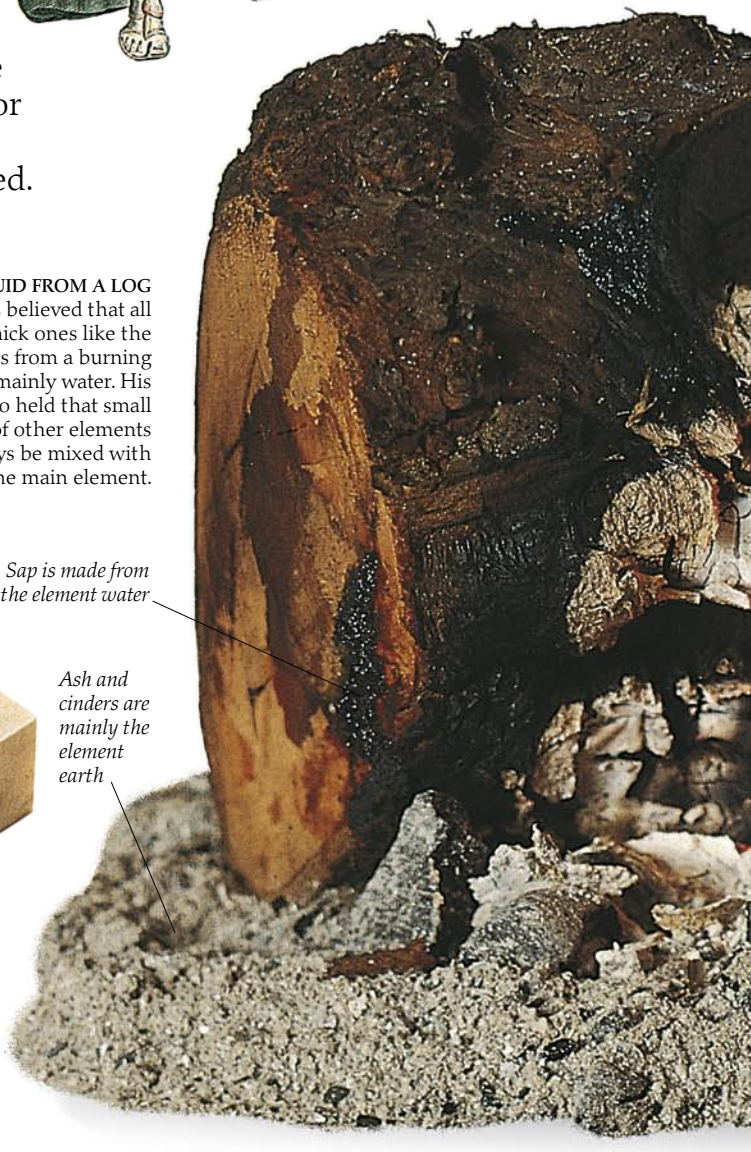
**WEARING SMOOTH**
Ancient philosophers thought that when objects such as coins and statues wore smooth with the passing of time they were losing tiny, invisible particles of matter.

**MODEL OF WATER**
Plato (4th century BC) thought that water was made up of icosahedrons, a solid shape with 20 triangular faces.

**LIQUID FROM A LOG**
Empedocles believed that all liquids, even thick ones like the sap that oozes from a burning log, were mainly water. His theory also held that small amounts of other elements would always be mixed with the main element.

**ELEMENTAL ATOMS**
Democritus developed the theory of atoms and combined it with the theory of elements. Like Plato, he thought there were only four shapes of atom, one for each element. He argued against the religious beliefs of his day, claiming that atoms moved randomly, and that there were no gods controlling the universe.

**MODEL OF EARTH**
Atoms of earth were thought by Plato to be cubes, which can stack tightly together to give strength and solidity.



*Sap is made from the element water*

*Ash and cinders are mainly the element earth*

**ASHES TO ASHES**
The theory of the elements suggested that ash and cinders were mainly made of the element earth, with a little of the element fire. At the end of the burning process, there was not enough fire left for more ash to be produced, but some fire remained for a while in the form of heat. The Greeks thought that the elements earth and water had a natural tendency to fall.

**THE FIVE ELEMENTS**
The human figure in this engraving is standing on two globes, representing earth and water, and is holding air and fire in his hands. The sun, moon, and stars are made of the ether, the fifth element.

**MODEL OF AIR**
Plato's model of an air atom was an octahedron, a solid figure with eight faces.

*Smoke is mostly air, with some earth in the form of soot mixed in*

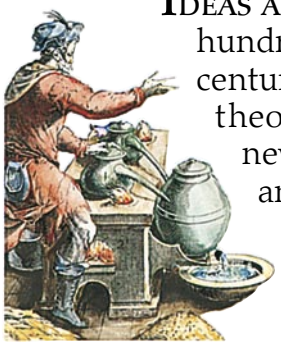
**NO SMOKE WITHOUT FIRE**
When a piece of matter is burned, the element air inside was thought to be released in the form of smoke. The Greeks thought that air, like fire, had a natural tendency to rise.

**MODEL OF FIRE**
According to Plato, the atom of fire was a solid shape with four sides called a tetrahedron.

**PENETRATING FLAMES**
The element fire could be seen most clearly in flames and sparks, but the Greeks thought that some fire was present in everything. Plato's model of the fire atom is sharp and pointed. This is because heat seemed to be able to penetrate virtually every piece of matter.

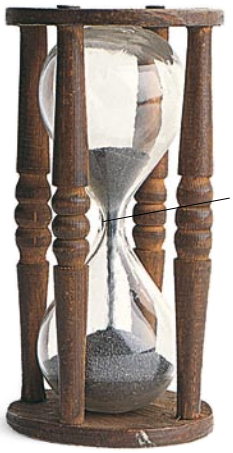
*Flames and sparks are the element fire*

# Investigating matter



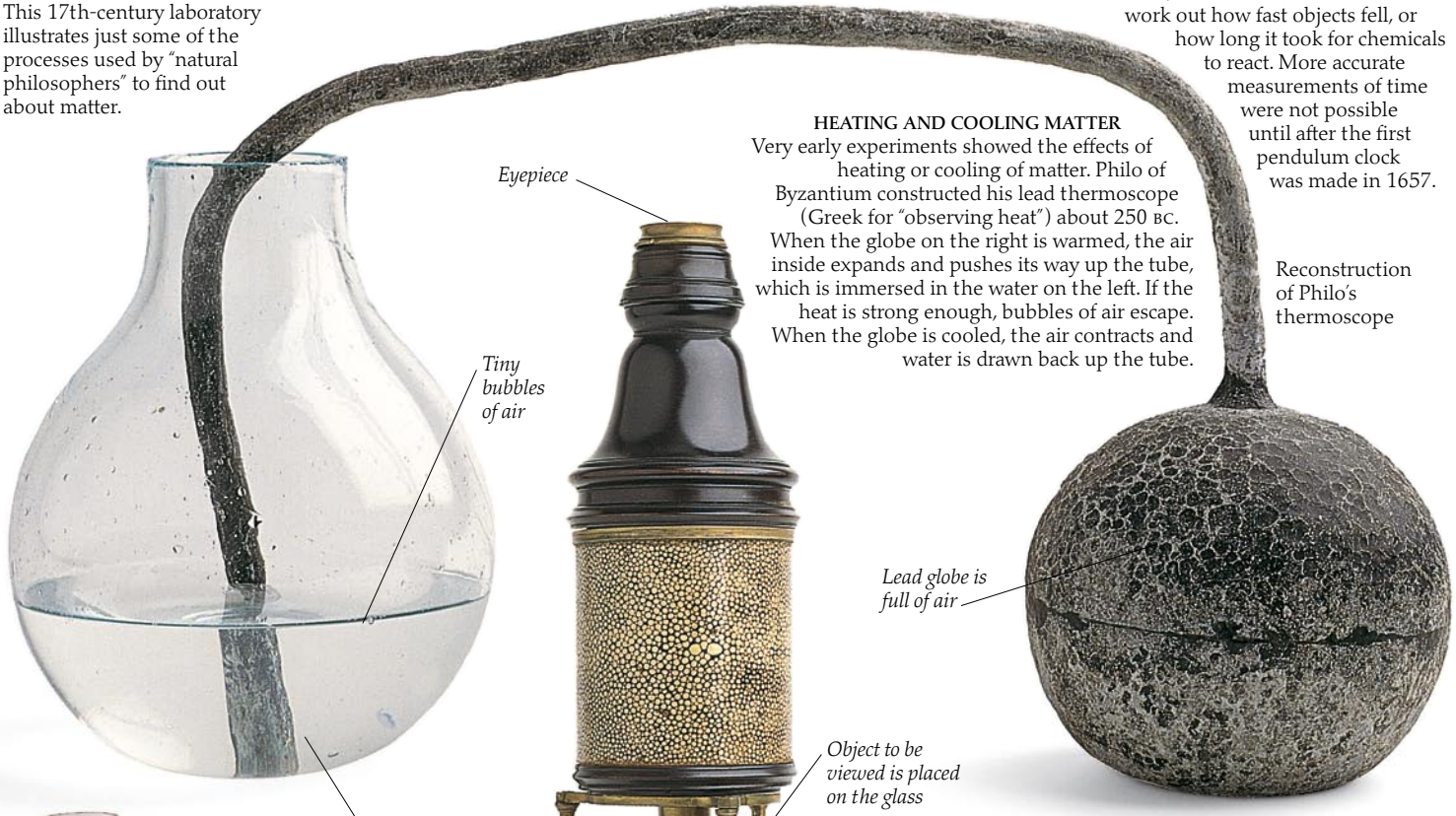
**Ideas about matter and how it behaved** changed little for hundreds of years. But in Europe during the 16th and 17th centuries "natural philosophers" looked again at the ancient theories about matter. They tested them, together with newer ideas about how matter behaved, by experiments and investigations, and used the newly invented microscope and telescope to look closely at matter. Measurements became more precise. News of discoveries was spread by the printing press. The scientific revolution had begun.

**LABORING IN THE LAB**
This 17th-century laboratory illustrates just some of the processes used by "natural philosophers" to find out about matter.




**SANDS OF TIME**
The sandglass was a simple timing device, which allowed scientists to work out how fast objects fell, or how long it took for chemicals to react. More accurate measurements of time were not possible until after the first pendulum clock was made in 1657.

**HEATING AND COOLING MATTER**
Very early experiments showed the effects of heating or cooling of matter. Philo of Byzantium constructed his lead thermoscope (Greek for "observing heat") about 250 BC. When the globe on the right is warmed, the air inside expands and pushes its way up the tube, which is immersed in the water on the left. If the heat is strong enough, bubbles of air escape. When the globe is cooled, the air contracts and water is drawn back up the tube.




Reconstruction of Philo's thermoscope

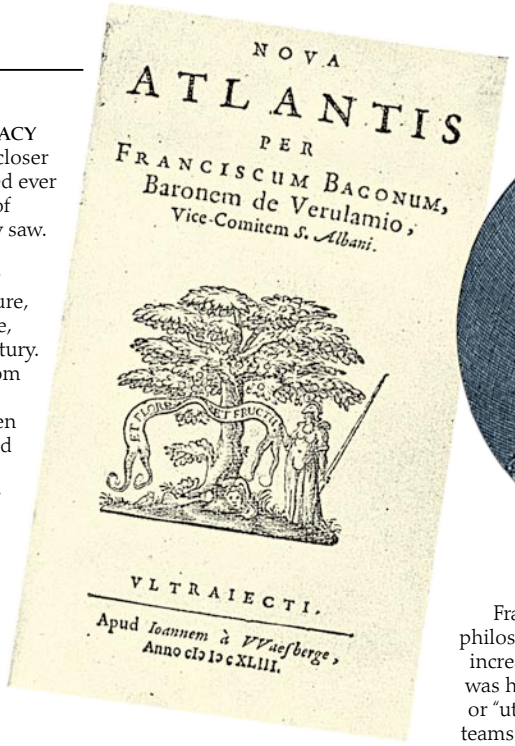


**MARKINGS FOR MEASURING**
Scientific investigations often involved measuring the exact amount of a liquid. This tall measuring cylinder has a scale of accurate markings for this purpose, while the specific gravity bottle has just one very accurate marking. When the liquid inside is weighed, its density can be calculated.

**SMALL WONDER**
Microscopes began to open up the world of the very small from the mid-1500s onward. In the mid-1600s Anton van Leeuwenhoek found that a single drop of pond water could contain 8 million "animalcules" – tiny but intricately constructed creatures and plants. The more elaborate microscope shown here was made by Edmund Culpeper of London, in about 1728. It used a tilting mirror, visible at the bottom, to reflect light onto a specimen mounted above it on glass.

Enlarged view of a deathwatch beetle


**DEGREES OF ACCURACY**
As scientists looked closer at matter, they needed ever more accurate ways of measuring what they saw. This thermometer, a device for measuring changes in temperature, was made in Florence, Italy, in the 18th century. The bulb at the bottom contained alcohol, which expanded when it became warmer and moved along the coiled tube. The tube is marked with dots at equal intervals.


NOVA
ATLANTIS
PER
FRANCISCUM BACONUM,
Baronem de Verulamio,
Vice-Comitem S. Albani.

VLTRAIECTI,
Apud Ioannem à Waesberge,
Anno cIↃ IↃ cXLIII.

**SCIENTIFIC IMPROVEMENTS**
Francis Bacon (1561-1626), the English philosopher, hoped that the new science could increase human well-being. *The New Atlantis* was his 1626 account of an imaginary society, or "utopia," where the government organized teams of scientists to conduct research and use the results to improve industry.


# Alchemy

Before the scientific revolution of the 17th century, the closest approach to a systematic study of matter was alchemy – the "science" of changing one substance into another. This was studied in Egypt, China, and India at least as early as the 2nd century BC, and from the Middle East it eventually reached Europe. Alchemists learned much from the practical skills of dyers and metalworkers, and borrowed various ideas from astrologers. They tried, without success, to change "base" metals, such as lead, into precious ones, such as silver or gold. This series of operations was described as "killing" the metal and then "reviving" it. Alchemists also attempted to make the elixir of life, a potion that would give them the secret of everlasting life.

**QUEST FOR GOLD**
Alchemists used all kinds of scientific instruments and chemical processes in their mystical quest for gold. The laboratory above was imagined by a 19th-century painter.

Spoutlike alembic sits on the cucurbit

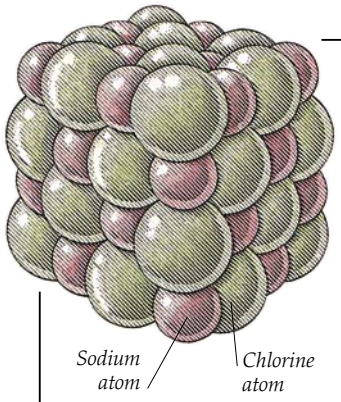
Alembic and cucurbit

**PURE MATTER**
Cucurbits and alembics were used by many alchemists to purify liquids. As the cucurbit was heated, vapor from the liquid inside rose to the top, then cooled and condensed. The pure liquid dripped from the alembic and was then collected.

**HANGING IN THE BALANCE**
Scales are one of the most basic of measuring instruments. The weight at the right of these Chinese scales is moved along the longer arm until it balances the object in the pan. This particular method is quick, convenient, and fairly accurate. It was not until the 17th century that chemists realized that accurately weighing the substances involved in a chemical reaction is crucial to understanding what is going on.

Greek lead weight

# Solid matter



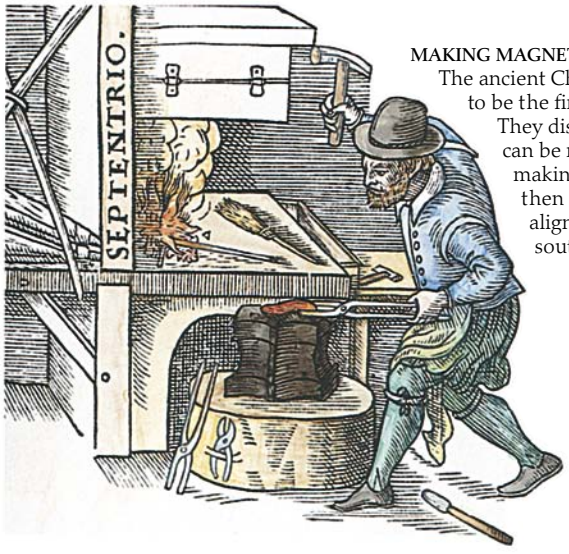

**HELD IN PLACE**
As in most solids, the atoms (pp. 34-35) in this model of salt hold each other firmly in place, and form a regular pattern.

EVER SINCE PEOPLE began to observe the world carefully, they have classified matter into three main states – solids, liquids (pp. 18-19), and gases (pp. 20-21). A piece of solid matter has a fairly definite shape, unlike a liquid or a gas. Changing the shape of a solid always requires a certain amount of force, which can be either large or small. Squeezing or stretching a solid can change its volume (the amount of space it takes up) but generally not by very much. When they are heated, most solids will turn to liquid, then to gas as they reach higher temperatures. However, some solids such as limestone (pp. 36-37) decompose when they are heated. Crystals (pp. 14-15) and metals (pp. 16-17) are two of the most important kinds of solid.

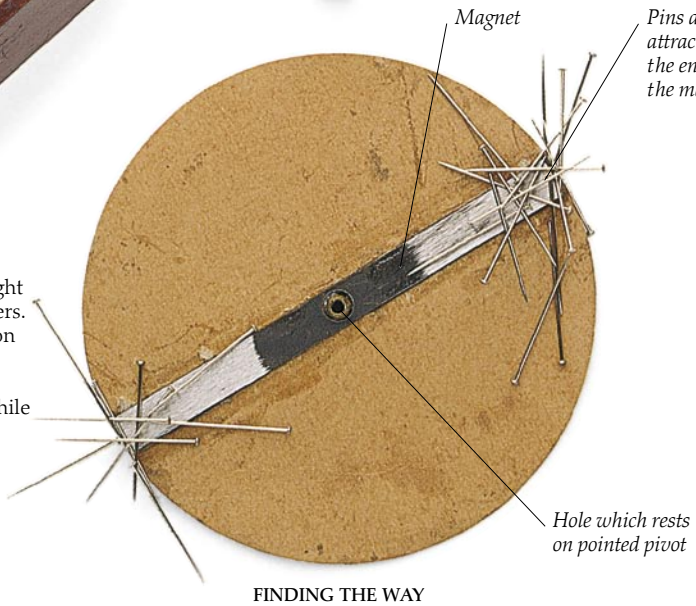

**SOLID STRENGTH**
Brass, which is a combination of metals, or an alloy (pp. 16-17), is made of copper and zinc. It is used for the compass's gimbal ring, mounting ring, and pivot. Brass is strong, so the gimbal ring's mountings will not quickly wear out. Like many metals, brass is not magnetic, and will not interfere with the working of the compass needle.

**SOLID PROPERTIES**
Like most artificial objects, this 19th-century mariner's compass contains several kinds of solids. The compass has been taken apart on these two pages to reveal four solids – metal, cardboard, wood, and glass. All the solids in the compass have been chosen for their special and varied properties.

Mariner's compass in its protective wooden box



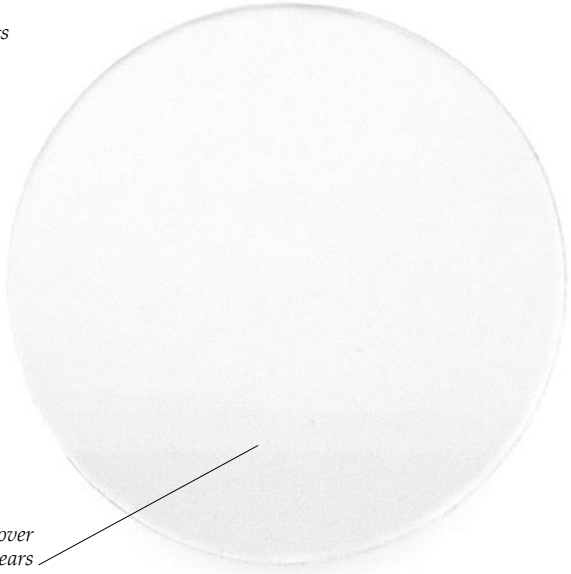

**MAKING MAGNETS**
The ancient Chinese are thought to be the first magnet makers. They discovered that iron can be magnetized by making it red-hot and then letting it cool while aligned in a north-south direction.




**FINDING THE WAY**
Beneath the compass card is a magnet, made either of iron or a rock called a lodestone. Magnets attract or repel each other, and also respond to the earth's magnetic poles. They tend to swing into a north-south line if they are free to move. The compass showed the mariner the angle between the direction of the ship and the north-south direction of the magnet.

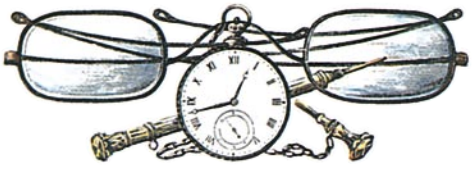
**SIZE AND STRENGTH**
Galileo Galilei (1564-1642) studied materials' strength and showed that there is a limit to land animals' size. If the largest dinosaur had doubled in size, its bones would have become larger and stronger. However, the increase in the dinosaur's weight would have been even greater, making its bones snap.

**AT FULL STRETCH**
Many solids are elastic – after being stretched or squeezed, they return to their original shape. A rubber band, for example, can be stretched to more than double its length and then return to its original length. But if a material is distorted too much its shape may be permanently altered.

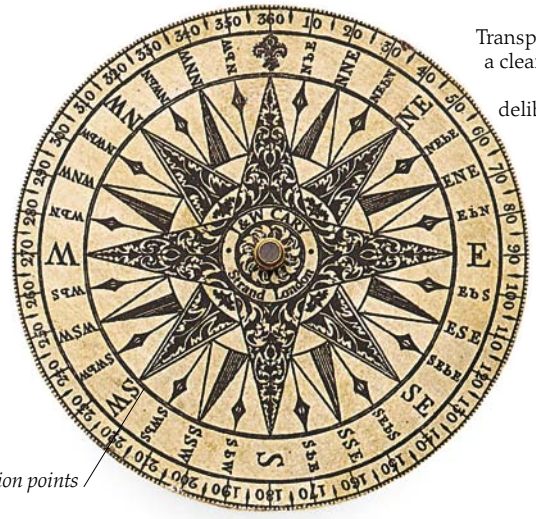




**SEEING THROUGH THINGS**
The top of the compass needs to be transparent and strong. It is made of glass – halfway between a solid and a liquid (pp. 24-25). Glass may seem rigid, but over hundreds of years it gradually flows and becomes distorted. Most solids block light completely, but the clearest kinds of glass absorb little of the light passing through them.

**QUALITIES OF WOOD**
The protective container of the compass needs to be strong, and to be rigid (keep its shape). Wood has many different qualities – the wood used for this container is fairly hard and long-lasting. Yet it is also soft and light enough to be easily worked with metal tools, and can be carved to form a smooth bowl shape.

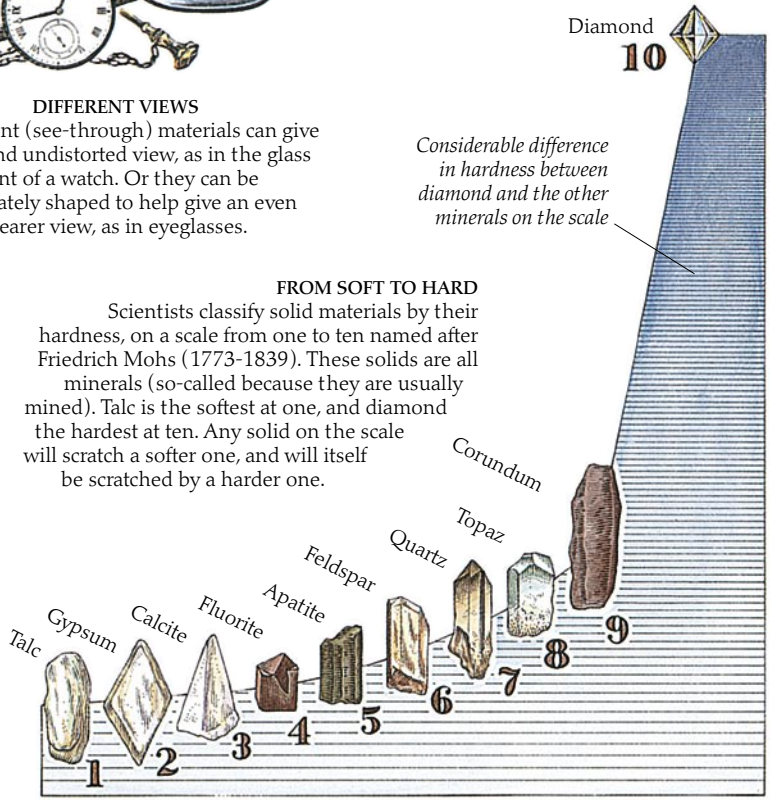


**DIFFERENT VIEWS**
Transparent (see-through) materials can give a clear and undistorted view, as in the glass front of a watch. Or they can be deliberately shaped to help give an even clearer view, as in eyeglasses.




**PAPER POINTERS**
The compass points are printed on paper or cardboard. Paper is made by pulping up wood and treating it to make it soft and flexible. It consists of countless fibers, and absorbs ink well because the ink lies in the spaces between the fibers.

**FROM SOFT TO HARD**
Scientists classify solid materials by their hardness, on a scale from one to ten named after Friedrich Mohs (1773-1839). These solids are all minerals (so-called because they are usually mined). Talc is the softest at one, and diamond the hardest at ten. Any solid on the scale will scratch a softer one, and will itself be scratched by a harder one.

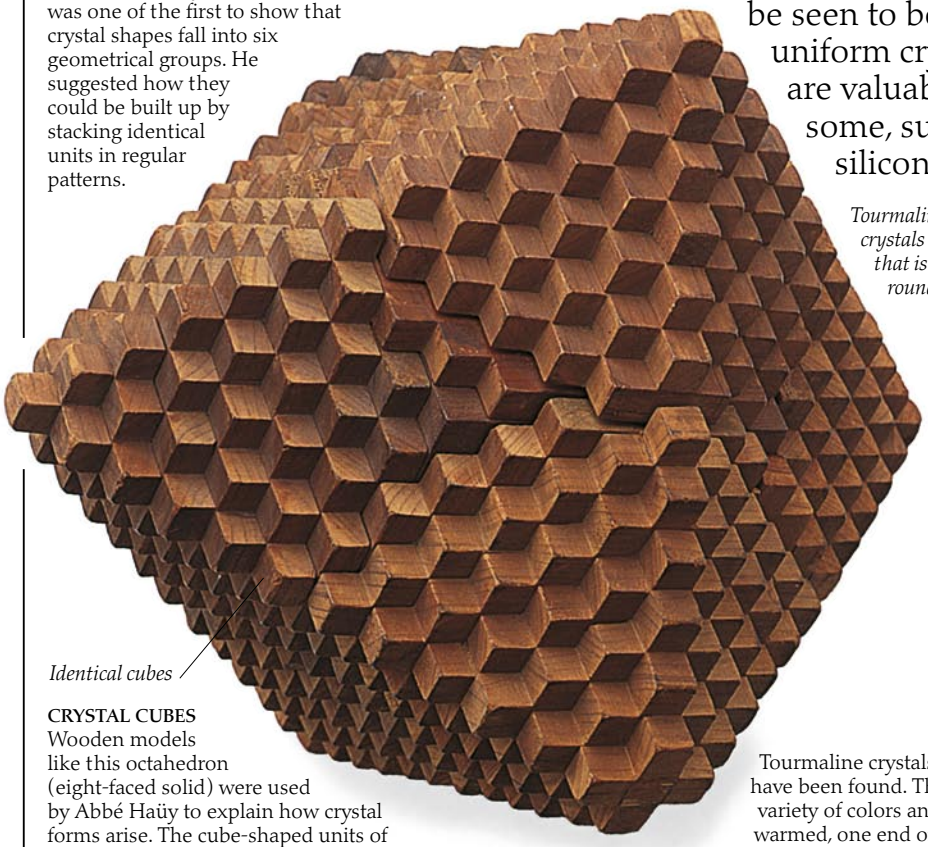


# The world of crystals

**SIX SHAPES**
Abbé René Haüy (1743-1822) was one of the first to show that crystal shapes fall into six geometrical groups. He suggested how they could be built up by stacking identical units in regular patterns.

CRYSTALS HAVE BEEN VIEWED with awe since ancient times. They are often very beautiful, and their shapes can differ widely, yet all crystal forms are of just six basic kinds. The orderly shape of each crystal is created by the arrangement of the atoms (pp. 34-35) inside. With the help of powerful microscopes, many objects and materials that seem irregularly shaped to the naked eye, such as stalactites and most metals, can be seen to be masses of tiny uniform crystals. Many crystals are valuable in industry, and some, such as quartz (used in watches) and silicon (used in computers), can be made in the laboratory.

**SCULPTED WATER**
Stalactites are mainly limestone, created by centuries of dripping water. The atoms in the limestone have arranged themselves in regular crystalline patterns.



*Identical cubes*

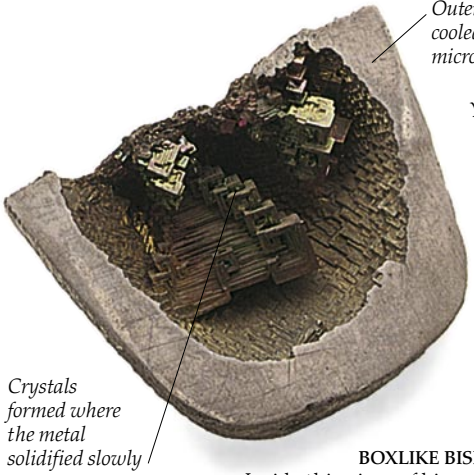
**CRYSTAL CUBES**
Wooden models like this octahedron (eight-faced solid) were used by Abbé Haüy to explain how crystal forms arise. The cube-shaped units of this crystal model are arranged in square layers, each larger than the previous one by an extra "border" of cubes.

*Tourmaline forms fine, long crystals with a cross-section that is triangular with rounded corners*

**HIGH-RISE CRYSTALS**
Tourmaline crystals up to 10 ft (3 m) long have been found. They can occur in a wide variety of colors and are prized as gems. If warmed, one end of a tourmaline crystal becomes positively charged, and the other end becomes negatively charged.

**THE EMERALD CITY**
Crystals are often used as symbols of perfection and power. The magical Emerald City appears in the 1939 film *The Wizard of Oz.*

*Outer part of the bismuth cooled fast and formed only microscopic crystals*



*Crystals formed where the metal solidified slowly*

**BOXLIKE BISMUTH**
Inside this piece of bismuth are intricate "nests" of crystal boxes, formed as the metal slowly solidified.

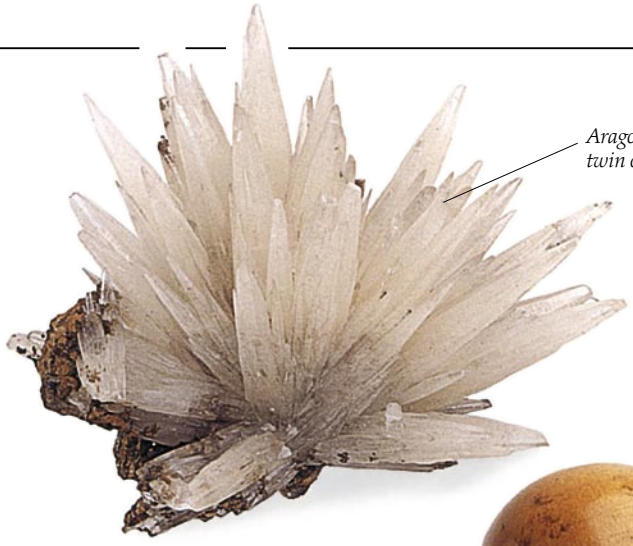
*Yellow sulfur crystals*

**MELLOW YELLOW**
At low temperatures, fairly flat sulfur crystals form. At high temperatures they are needle-shaped.

*Needle-shaped crystals formed where alloy solidified slowly*

*Outer part of alloy cooled fast and formed few crystals*

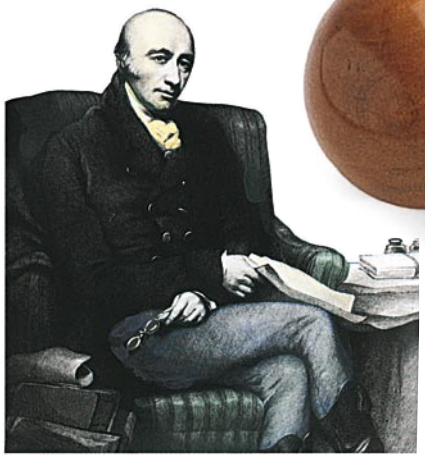
**METAL MIXTURE**
The thin, pointed crystals shown here are alloys (pp. 16-17) of copper and aluminum.




**AMAZING ARAGONITE**
Crystals of aragonite can be found in limestone caves and hot springs. They take many forms, such as fibers, columns, or needles. Their color is usually white, yellow, green, or blue.

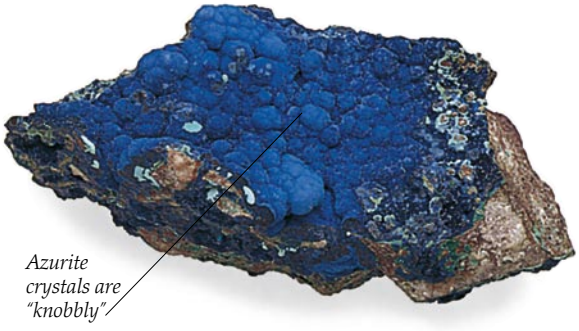
**EGG-SHAPED ATOMS**
In this model made by Wollaston, the atoms in the crystal are imagined to be egg-shaped. Each has six neighbors at the sides, forming a strong horizontal layer.

**LOOSE LAYERS**
If atoms in crystals are spheres, Wollaston realized that they would have neighbors on all sides. They would not form such strong layers as the atoms of the other shapes shown here.



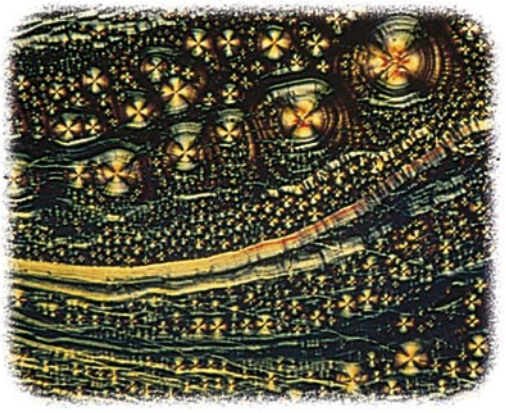
**MAKING CRYSTALS CLEAR**
William Hyde Wollaston (1766-1828) made important contributions to crystallography (the scientific study of crystals). He recognized that a cubic crystal, for example, did not have to be built from cubes. Instead, it could be assembled from atoms of other shapes, as in his wooden models shown on this page. Scientists now know that atoms can take very complicated shapes when they join together.

**FLAT ATOMS**
Wollaston thought that if crystal atoms are flat, they would link most strongly where their flat faces were in contact. They might form columns or fibers.

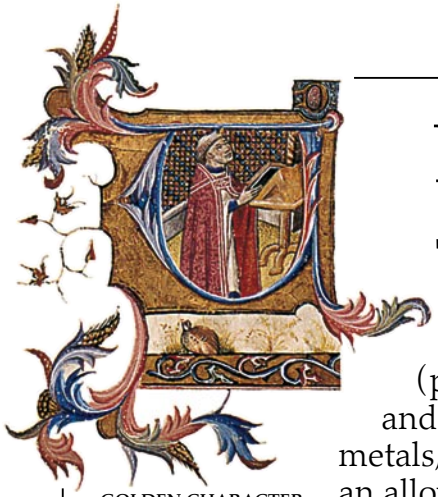



**BLUE IS THE COLOR**
The mineral azurite is blue, as its name implies. In the past azurite was crushed and used as a pigment. It contains copper and is found with deposits of copper ore. When azurite is made into a gem, it can be faceted – cut to display polished flat faces.

**LINING UP LIQUID CRYSTALS**
Some crystals are liquid. The particles in a liquid can be temporarily lined up in regular arrays when an electric or magnetic field is applied. The liquid crystals shown here were revealed under an electron microscope. The liquid affects light differently when the crystals form, and can change from being transparent to being opaque, or colored. In digital clocks and watches, calculators, or laptop computers, electricity is used to alter segments of the display from clear to dark, to generate the changing numbers or letters.

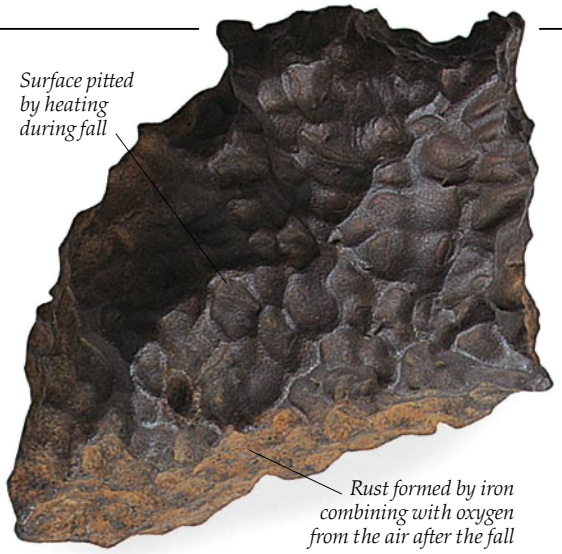


# Metals and alloys



**GOLDEN CHARACTER**
Gold is a precious metal. It is rare and does not tarnish. It can be beaten into sheets of gold leaf, which are used to decorate letters in illuminated manuscripts like the one above.

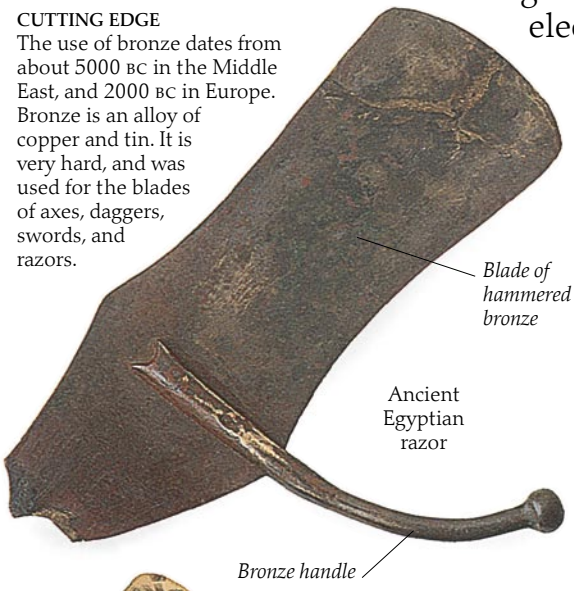
THE THREE METALS most widely used are iron, steel, and aluminum. Iron and aluminum are both metallic elements (pp. 32-33), but steel is a mixture of iron and carbon. Such a combination, either of metals, or of metals and non-metals, is called an alloy. Combining a metal with other substances (either metallic or non-metallic) usually makes it stronger. Most metals are found in ore (rock), combined with other elements such as oxygen and sulfur. Heating the ore separates and purifies the metal. When metals are pure they are shiny, can be beaten into shape, and drawn out into wires. They are not brittle, but are often rather soft. Metals are good conductors (carriers) of electric current and heat.




**HEAVENLY METAL**
A very pure iron comes from certain meteorites. They are bodies that have fallen to Earth from outer space and have been partly burned away by the friction of entering the Earth's atmosphere.

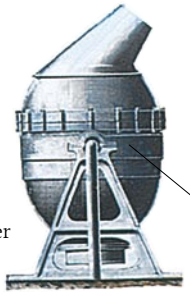

**LIQUID METAL**
The metal mercury, sometimes known as quicksilver, is a liquid at normal temperatures. It expands by a relatively large amount when warmed, and has long been used in instruments to measure temperature, such as this 18th-century thermometer.

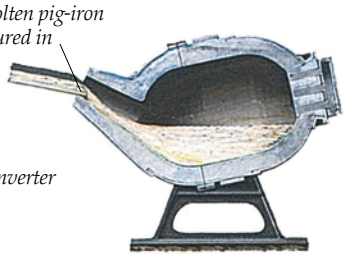
**CUTTING EDGE**
The use of bronze dates from about 5000 BC in the Middle East, and 2000 BC in Europe. Bronze is an alloy of copper and tin. It is very hard, and was used for the blades of axes, daggers, swords, and razors.

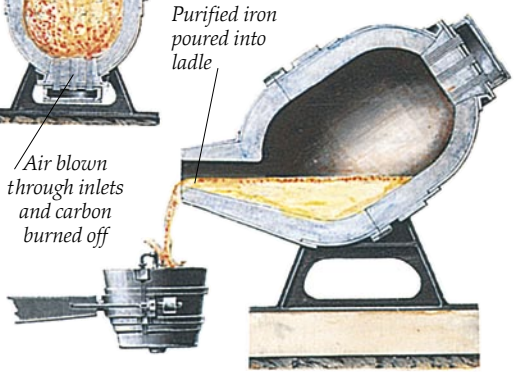




**HARD WORDS**
Aluminum makes up one-twelfth of the rock near the Earth's surface. It was discovered in 1809, but only came into widespread use after 1886. It is a very light metal, and was first used in jewelery and novelties, like this picture postcard. Aircraft parts are often made of aluminum alloys.

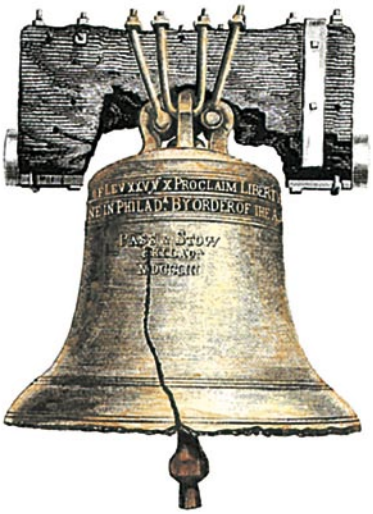


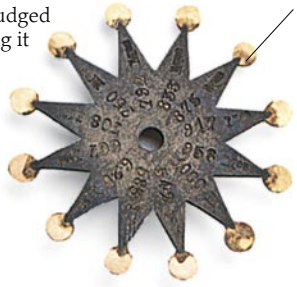

Henry Bessemer

**MAN OF STEEL**
Henry Bessemer (1813-1898) greatly speeded up the steel-making process in the mid-19th century with his famous converter. Air was blown through molten pig iron (iron ore that had been heated in a furnace with coal or wood). This burned off the carbon (pp. 40-41) from the coal or wood in a fountain of sparks. The purified iron, still molten, was tipped out of the converter, and measured amounts of carbon and metals, such as nickel, manganese, or chromium, were added. These other substances turned the molten iron into steel, an alloy that is renowned for its strength.



**BELL OF BRONZE**
Metals such as bronze are ideal for bells because they vibrate for a long time after being struck. From about 1000 BC bronze has been cast (poured in a molten state into a mold). Once cast, large bells must cool very slowly to prevent cracking. The Liberty Bell, which hangs in Philadelphia, Pennsylvania, weighs about 2,079 lb (943 kg), and is about 3 ft (1 meter) high. It was made in London and delivered in 1752, but it cracked and had to be recast twice before it was hung. It cracked again in 1835 and in 1846. Since then it has never been rung.

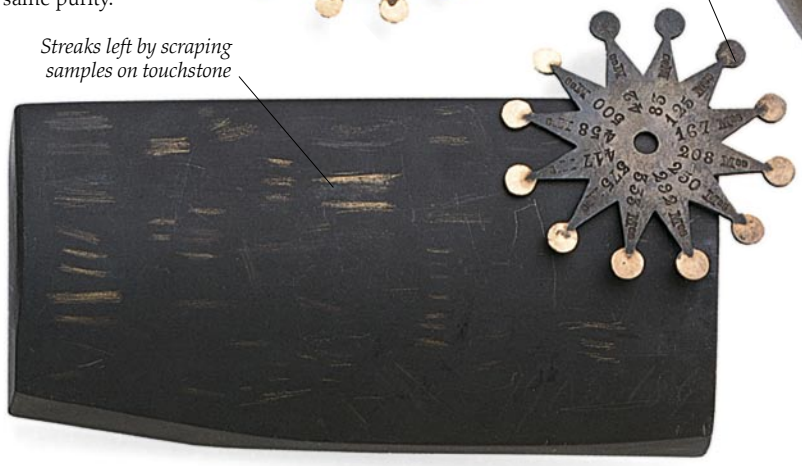
**PURE QUALITY**
Goldsmiths formerly judged gold's purity by scraping it on a type of dark rock called touchstone. Its streak was then compared with the streaks made by the gold samples on two "stars." The best match came from gold of the same purity.



*Sample has 875 parts of gold per thousand*

*Sample has 125 parts of gold per thousand*

*Streaks left by scraping samples on touchstone*



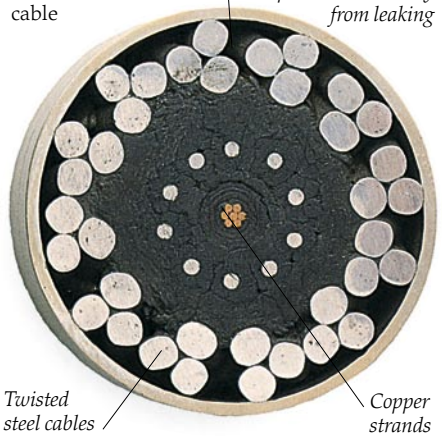

**MULTIPURPOSE METALS**
Various metals, each with its own particular job to do, are used in this old clock. The springs, chain, and cogwheels inside, which receive the most wear, are made of steel. The case is made of brass, an alloy of copper and zinc that is not so strong as steel. To make it look attractive, the brass has been gilded (coated with gold).

*Twisted steel cables*

**DEEP COMMUNICATION**
A telegraph cable 2,325 miles (3,740 km) long was first laid across the seabed of the Atlantic Ocean in 1850, linking Britain with the US. The outer part of a typical cable was a strong sheath of twisted steel cables. It would resist rusting even in seawater (a solution known to rust metals quickly).

Cross-section of transatlantic cable

*Rubberlike gutta-percha prevents electricity from leaking*

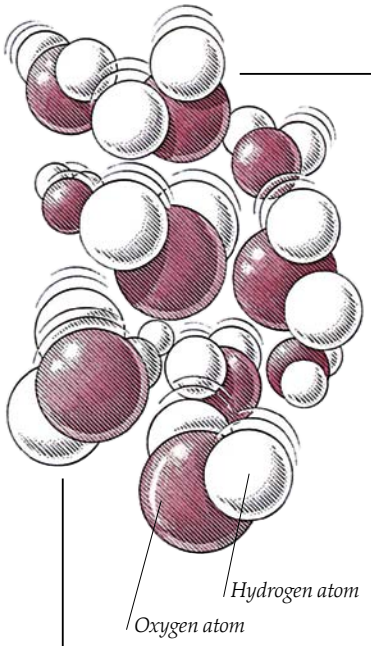


*Twisted steel cables*

*Copper strands*

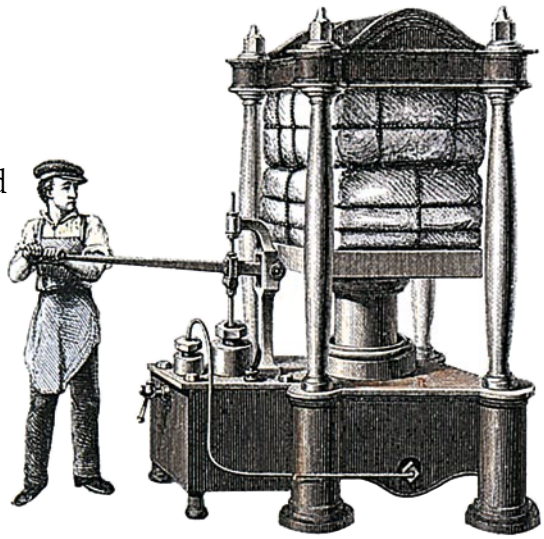
**OCEAN CURRENT**
A seven-stranded copper wire lies at the heart of the undersea cable. Copper was chosen for the wire because of its very useful properties. It is an excellent carrier of electric current and is easily drawn out into wires.

# Properties of liquids



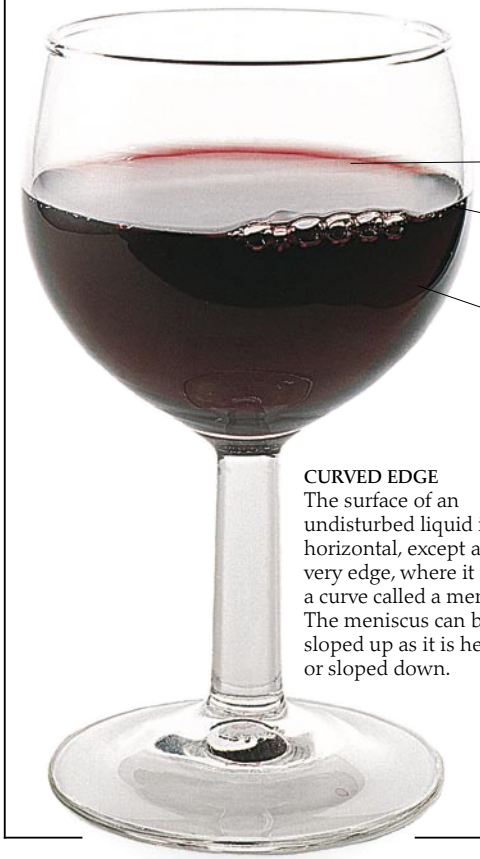

**SLIPPING AND SLIDING**
The smallest unit of water consists of one atom (pp. 34-35) of oxygen joined to two hydrogen atoms. These clusters of three atoms slide around each other in liquid water.

According to the Greeks who believed in the four elements, all liquids contain a large proportion of water (pp. 8-9). However, those who believed in atoms (pp. 34-35) thought that the atoms in a liquid could slide around one another, making the liquid flow to take the shape of its container. This is also the modern view. Liquid particles attract each other and keep close together, so they cannot be easily squeezed into a smaller volume or stretched out into a larger one. When a liquid is heated, however, the spacing between the particles generally increases in size, so the liquid expands. When a liquid is cooled, the reverse effect occurs, and the liquid contracts. It is possible for liquids to dissolve some solid substances. For example, salt placed in water seems to disappear very slowly. In fact the salt breaks up into individual atoms of sodium and chlorine (pp. 50–51). The ions spread out through the water, forming a mixture (pp. 26-27) called a solution of salt in water. Liquids can also dissolve gases and other liquids.

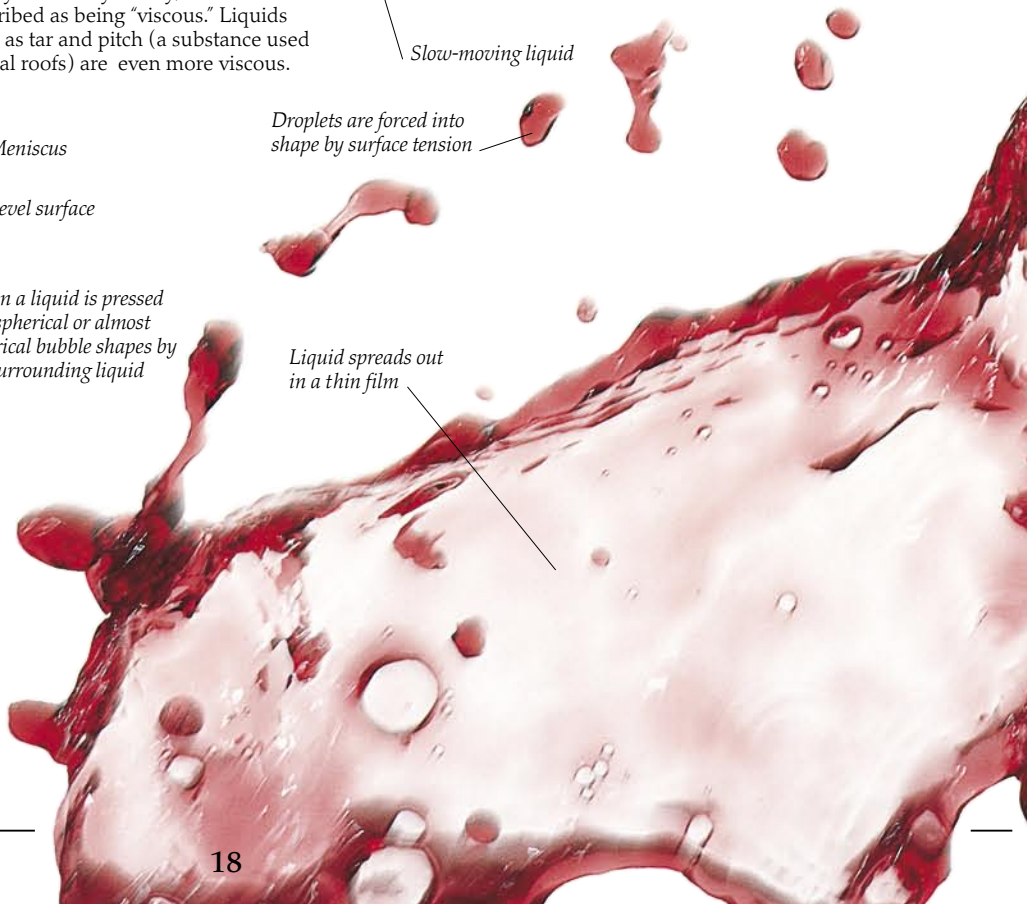


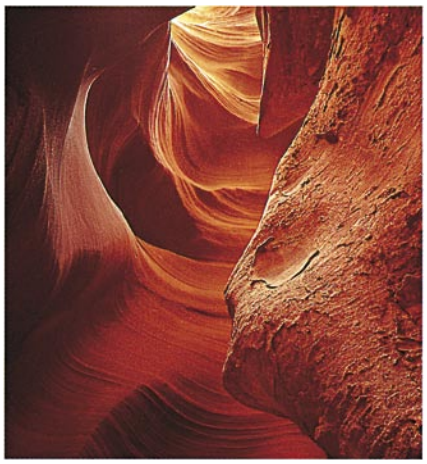
**PRESSING MATTER**
Most liquids, particularly water and oil, act as good transmitters of pressure. In 1795 Joseph Bramah (1749-1814) patented his hydraulic press, in which compressed fluid multiplied the force that could be exerted by a human operator.


**SLOW FLOW**
Some liquids flow easily, but honey flows very slowly, and is described as being "viscous." Liquids such as tar and pitch (a substance used to seal roofs) are even more viscous.




**CURVED EDGE**
The surface of an undisturbed liquid is horizontal, except at the very edge, where it forms a curve called a meniscus. The meniscus can be sloped up as it is here, or sloped down.





**WORN DOWN BY WATER**
Given sufficient time, flowing liquids wear away solid surfaces, even rocks. The abrasive effect is increased when the liquid carries solid particles of rock and mud. Some rocks, such as clays and sandstones, have a low resistance to erosion. This canyon in the Arizona desert has been worn away by 10,000 years of flash floods.

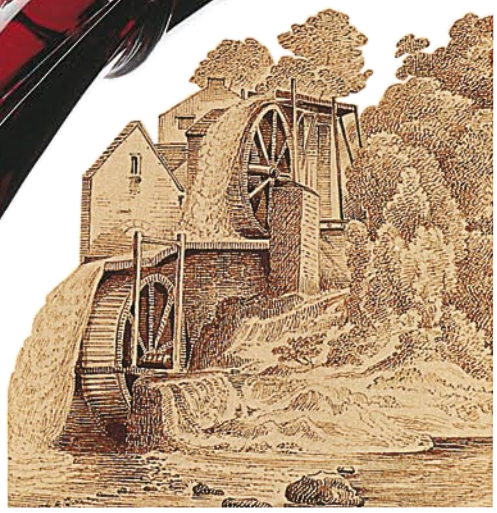
**UPLIFTING MATERIAL**
Because a liquid can flow, an object can be pushed down into it, forcing some of the liquid aside. But the displaced liquid tries to flow back, pushing the object upward. The object then seems lighter than the liquid, and floats, like this boat.

*Narrow neck of vessel causes liquid to speed up as it flows through*

*Fast-moving liquid*

*Liquid takes the shape of its container*

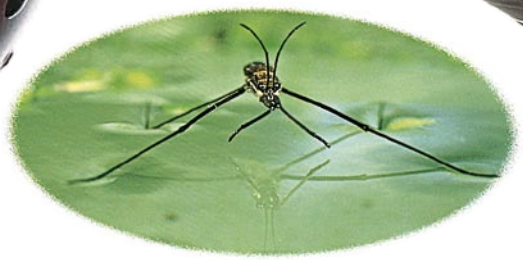
**THE STRENGTH OF MOVING LIQUIDS**
A stream of liquid can deliver a powerful force – a tsunami, or "tidal wave," can sweep away towns. Slower-moving liquid has time to break up and flow round obstacles, and does them less damage. Where a liquid has escaped from a container, surface tension (the inward pull at the surface) tries to pull it into shape. But because it is a relatively weak force, surface tension can pull only small amounts into drops – larger quantities of liquid are chaotic and formless.



**WATER POWER**
Streams and rivers have been used to turn waterwheels since ancient times. In 18th-century Britain water-powered looms featured heavily in the Industrial Revolution. Today, water from lakes, reservoirs, or the sea is used to turn electricity-generating turbines worldwide.

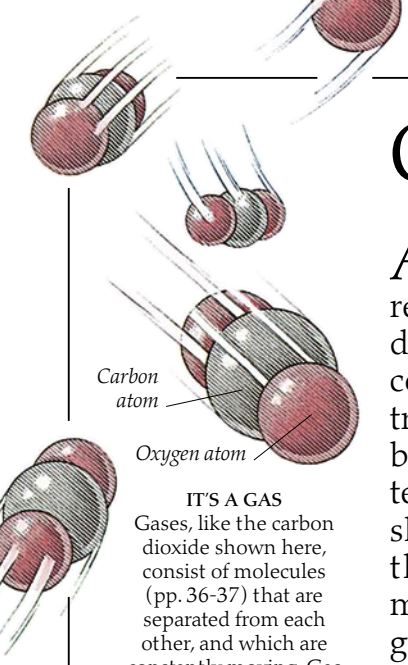
*Level surface*

**BRIMMING OVER**
The tiny particles that make up a liquid are held together by their attraction to each other. Surface tension makes the surface of a liquid behave like the tight elastic skin of a balloon. The wine in this glass is above the brim, but surface tension stops it from overflowing.



**WALKING ON WATER**
Surface tension lets this insect's feet walk instead of swim; its feet make dents in the water but don't go through.

# Gases and their properties




**IT'S A GAS**
Gases, like the carbon dioxide shown here, consist of molecules (pp. 36-37) that are separated from each other, and which are constantly moving. Gas molecules are usually complex, made up of atoms (pp. 34-35) that are closely bound together.

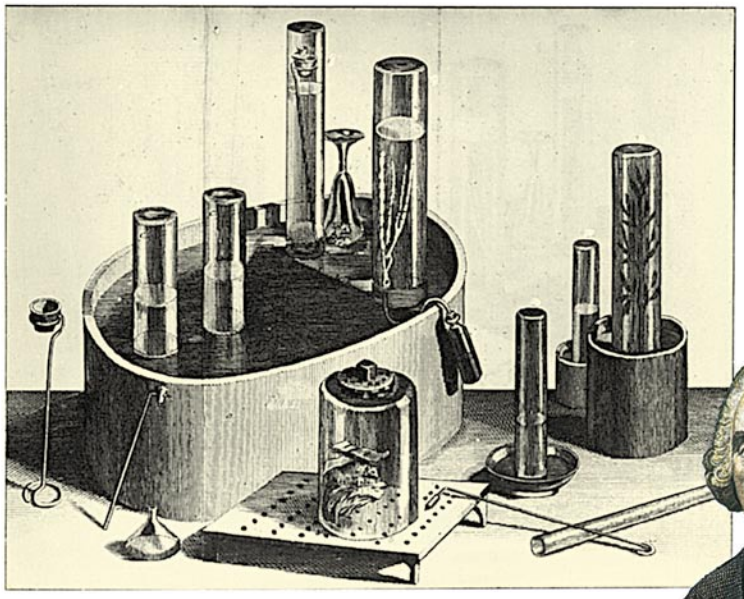
ANCIENT PHILOSOPHERS WERE PUZZLED by the exact nature of gases. They realized air was not empty space. Some guessed the smell of a perfume was due to the spreading of tiny particles, and that frost was formed by the condensation of invisible water vapor. Many observed that the wind bent trees and vigorous bubbling made water froth. These early philosophers believed there was a single element of air (pp. 8-9), which had "levity," a tendency to rise. In the 17th century Evangelista Torricelli (1608-1647) showed that air, like solids and liquids, can be weighed. In the next century, chemists showed that air is a mixture of gases, and identified the gases given off in chemical reactions. These newly discovered gases were soon put to use; for instance, gas obtained from coal produced light and heat.




**AIRLESS EXPERIMENTS**
The airpump shown here was built by Francis Hauksbee (1666-1713). The lever was worked to operate twin pistons, which removed air from the glass dome. Experiments could then be performed under the dome in an airless environment. The first airpump was made in the 1650s by Otto von Guericke (1602-1686), to demonstrate the strength of air pressure.

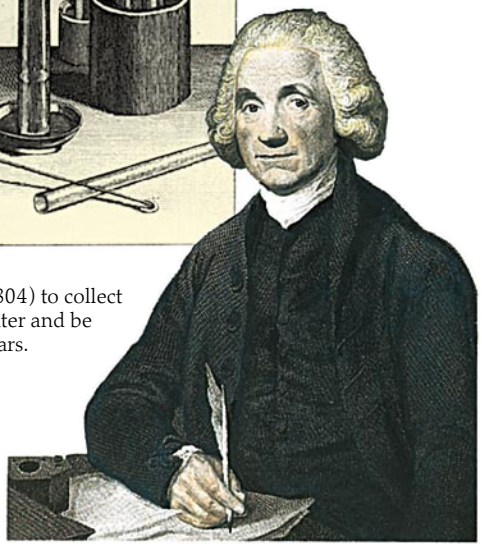

**LIBERATING OXYGEN**
When a solid is heated, it can often give off a gas. The crystals of potassium permanganate are composed of potassium, manganese, and oxygen. When heated, the crystals break down into other substances, and give off oxygen gas. The oxygen occupies a much larger volume as a gas than when it was combined in the solid, and escapes from the end of the tube. The gas is less dense than water, and bubbles to the top of the collecting jar.

**PRESSING FORCE**
A barometer measures changes in atmospheric pressure. The early barometer made by Evangelista Torricelli had a mercury-filled upright glass tube. The tube's open end dipped in a bowl of mercury. Atmospheric pressure forced the mercury down in the bowl, and balanced the weight of the mercury in the tube.

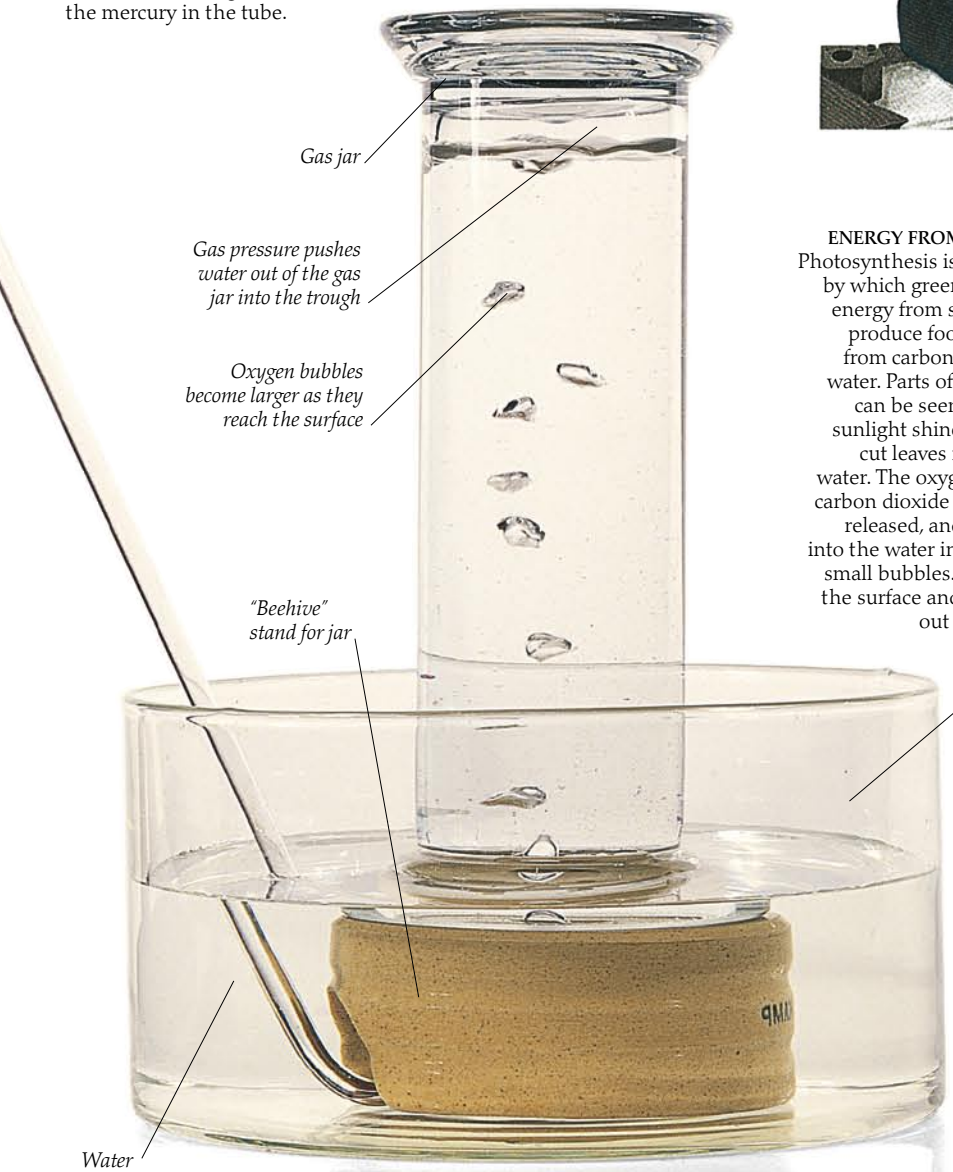


**A VALUABLE COLLECTION**
This apparatus was used by Joseph Priestley (1733-1804) to collect gases. The gases would bubble up through the water and be collected for experimentation in the glass jars.

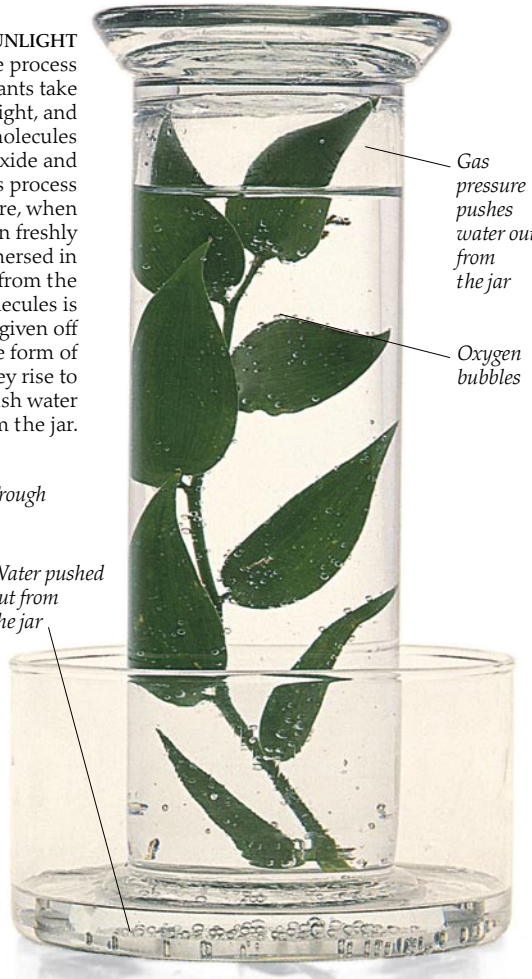
**HIGH ACHIEVER**
Jacques Charles (1746-1823) discovered an important law about the expansion of gases when heated (p. 39). In 1783 he took part in the first flight in a hydrogen balloon. Hydrogen is very light and also highly flammable, but was still being used in airships in the 1930s.



**GAS WORKER**
In 1775 Joseph Priestley discovered oxygen during his work with mercuric oxide. He found that oxygen supported breathing and burning, but did not recognize its exact nature. Using carbon dioxide from a local brewer to make water fizzy, he invented soda water.



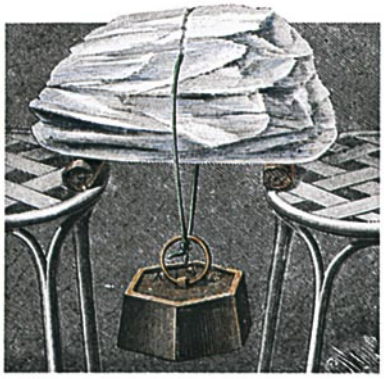

**ENERGY FROM SUNLIGHT**
Photosynthesis is the process by which green plants take energy from sunlight, and produce food molecules from carbon dioxide and water. Parts of this process can be seen here, when sunlight shines on freshly cut leaves immersed in water. The oxygen from the carbon dioxide molecules is released, and is given off into the water in the form of small bubbles. They rise to the surface and push water out from the jar.



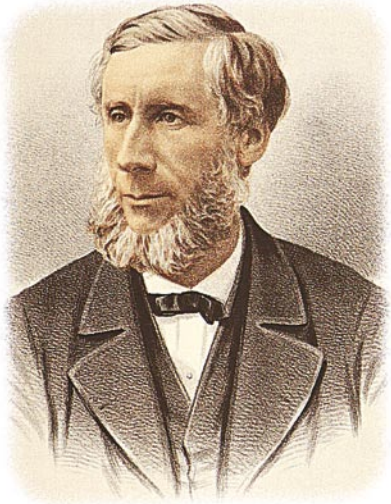
# Changes of state

**DROPPING LEAD**
Bullets and lead shot used to be made by letting drops of molten lead fall from the top of a "shot tower." While still liquid, the lead droplets formed spheres, and then "froze" in this shape.

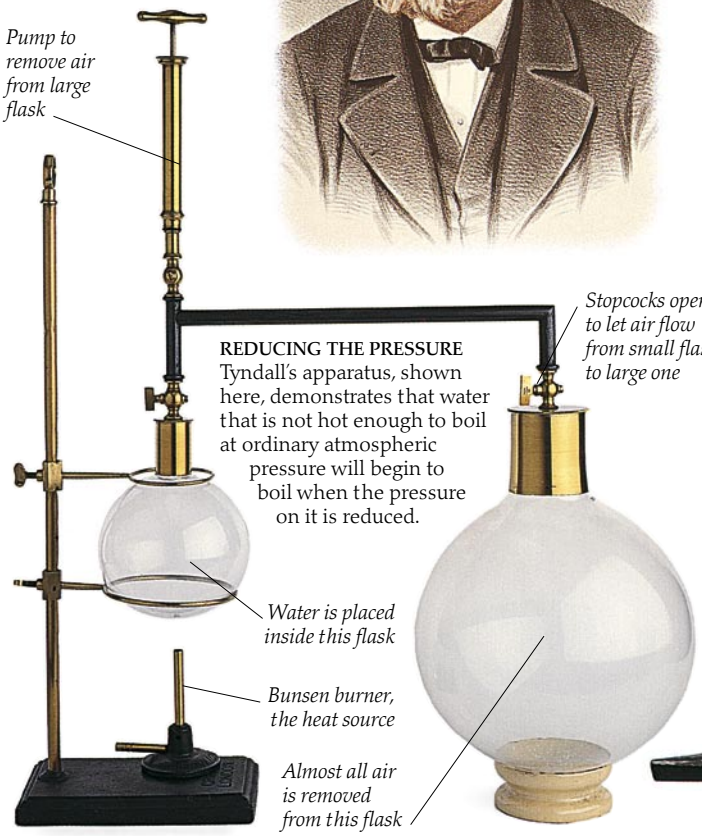
**MATTER CAN BE ALTERED** in various ways. Heating a solid to a temperature called its melting point will make it change state – it will turn into a liquid. Heating a liquid to a temperature called its boiling point has a similar effect – the liquid will change state and turn into a gas. It is possible to affect both the melting and the boiling point of matter. For example, if an impurity such as salt is added to ice, the melting point of the ice is lowered. The mixture (pp. 26-27) of salt and ice will melt, while pure ice at the same temperature will remain frozen. If salt is added to water, it raises the boiling point, and the water boils at a higher temperature. Pressure can also affect the state of matter. Where air pressure is low, the boiling point of water is lowered. An increase in pressure will lower the melting point of a solid.



**YIELDING TO PRESSURE**
Where a wire presses on ice, the melting point is lowered, and the ice melts. The wire cuts through the ice, which freezes again as the wire passes.

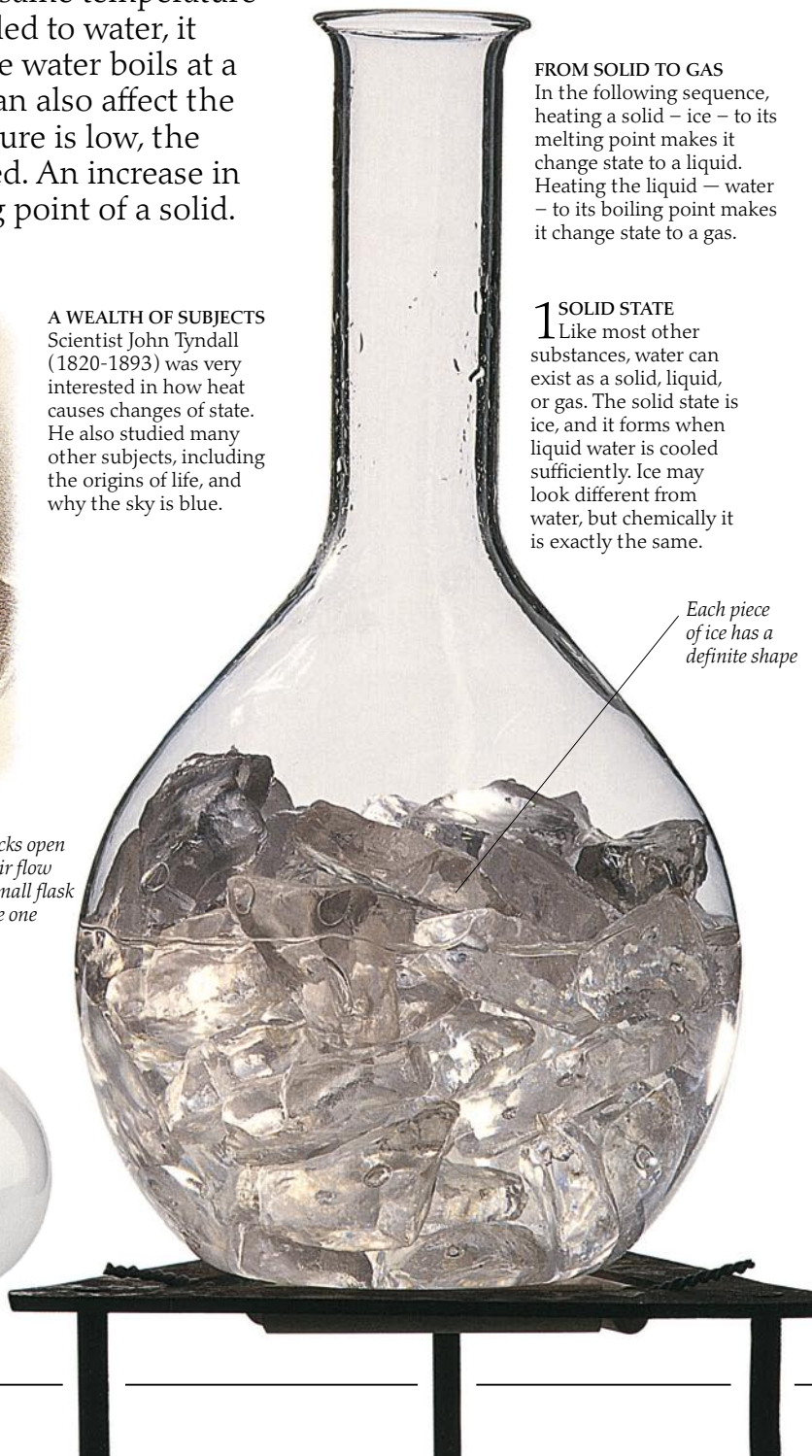


**A WEALTH OF SUBJECTS**
Scientist John Tyndall (1820-1893) was very interested in how heat causes changes of state. He also studied many other subjects, including the origins of life, and why the sky is blue.

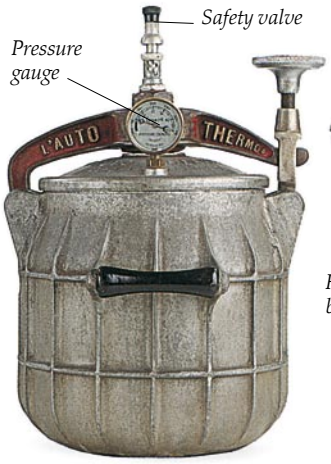



**REDUCING THE PRESSURE**
Tyndall's apparatus, shown here, demonstrates that water that is not hot enough to boil at ordinary atmospheric pressure will begin to boil when the pressure on it is reduced.

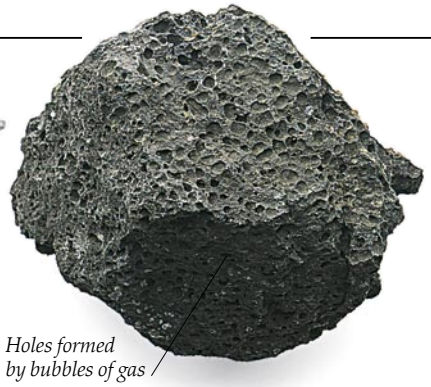
**FROM SOLID TO GAS**
In the following sequence, heating a solid – ice – to its melting point makes it change state to a liquid. Heating the liquid — water – to its boiling point makes it change state to a gas.




**1 SOLID STATE**
Like most other substances, water can exist as a solid, liquid, or gas. The solid state is ice, and it forms when liquid water is cooled sufficiently. Ice may look different from water, but chemically it is exactly the same.



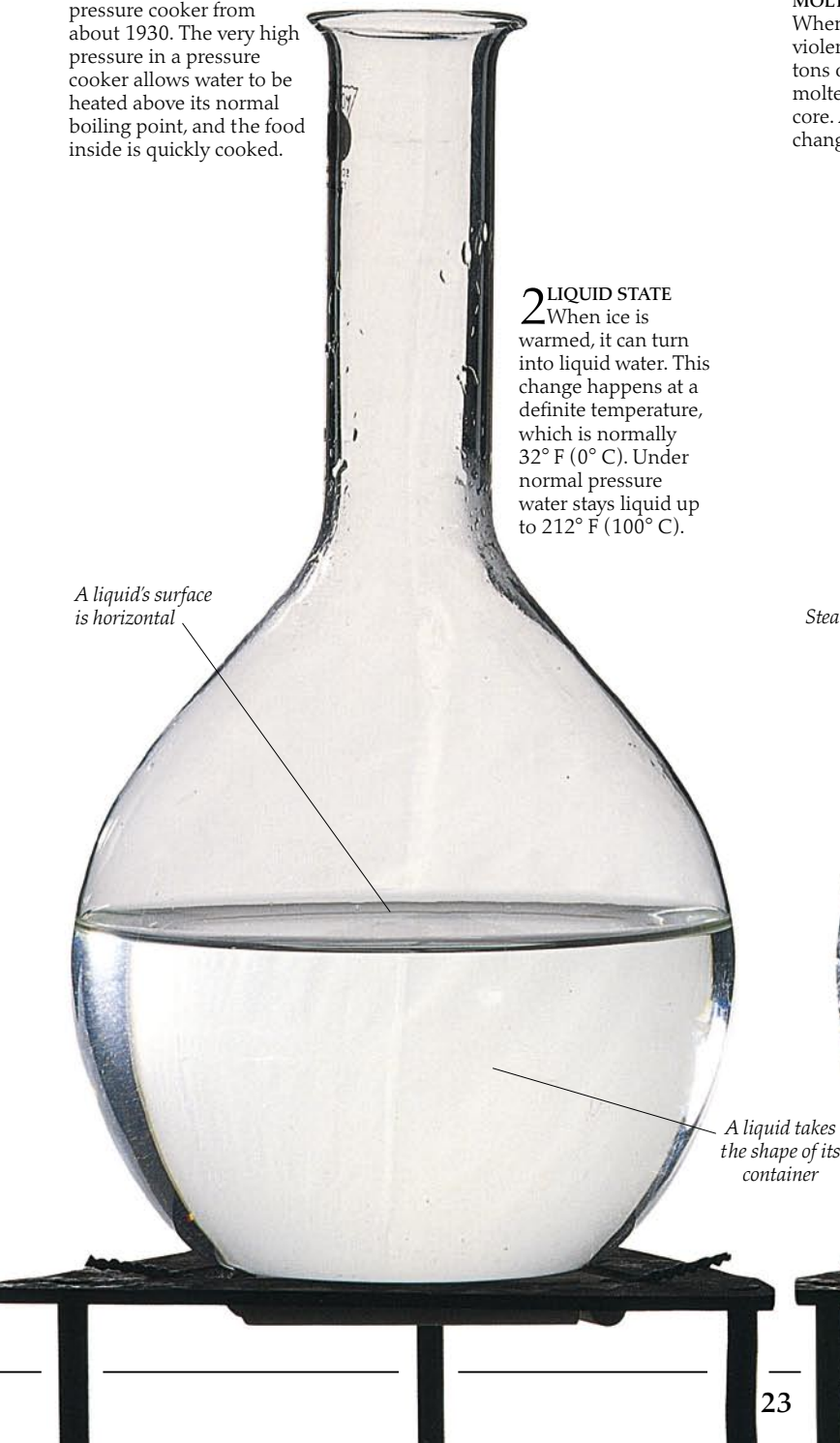

**PRESSURE AT WORK**
This is a cast-aluminum pressure cooker from about 1930. The very high pressure in a pressure cooker allows water to be heated above its normal boiling point, and the food inside is quickly cooked.




**STONE FROM A VOLCANO**
Pumice stone is molten lava which has cooled very quickly. It is honeycombed with holes, which are "frozen-in" bubbles of gas.

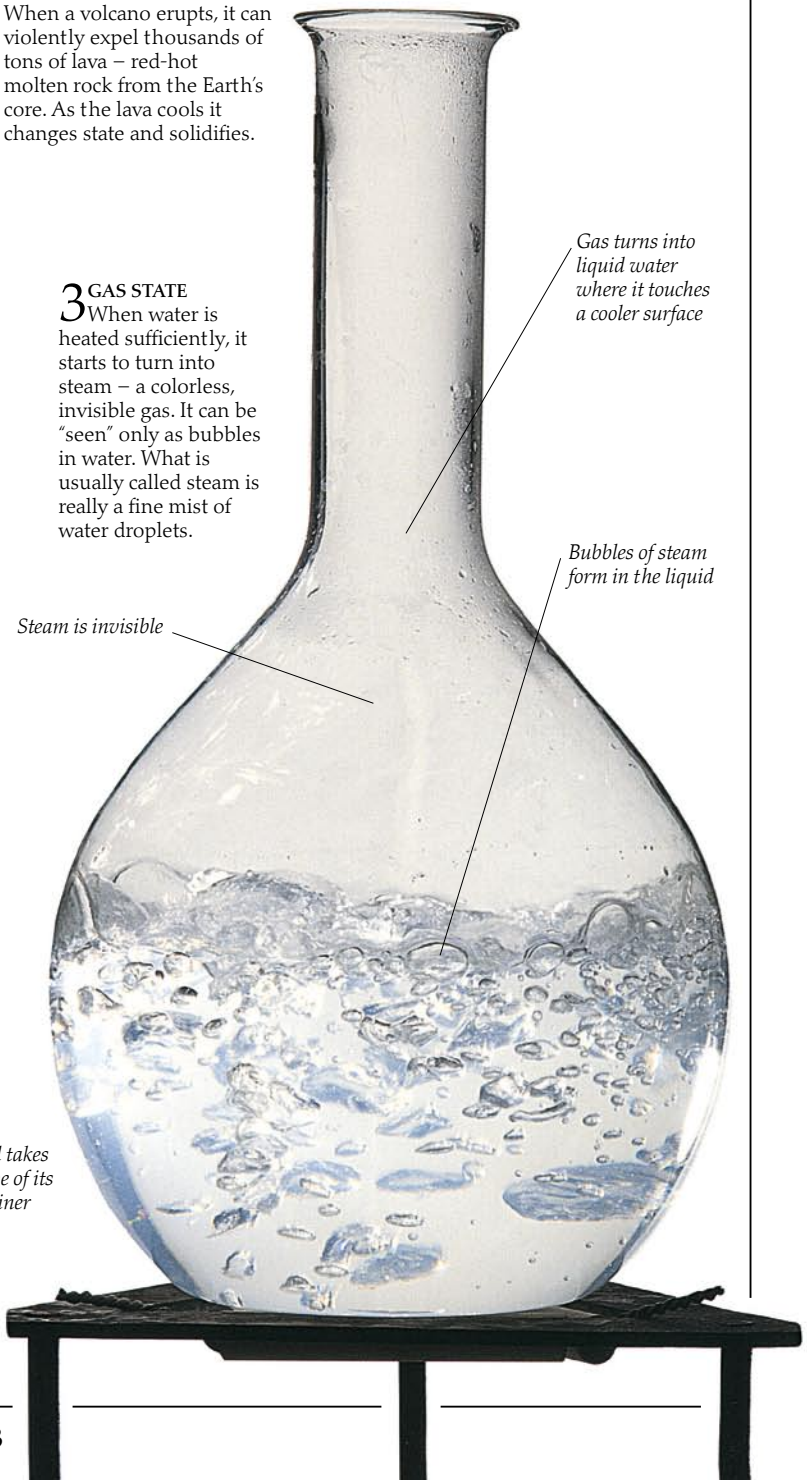
**MOLTEN MOUNTAIN**
When a volcano erupts, it can violently expel thousands of tons of lava – red-hot molten rock from the Earth's core. As the lava cools it changes state and solidifies.

**HIDDEN HEAT**
Joseph Black (1728-1798) measured the heat needed to turn a solid into a liquid, or a liquid into a gas. He called this heat "latent," or hidden.




**2 LIQUID STATE**
When ice is warmed, it can turn into liquid water. This change happens at a definite temperature, which is normally 32° F (0° C). Under normal pressure water stays liquid up to 212° F (100° C).

**3 GAS STATE**
When water is heated sufficiently, it starts to turn into steam – a colorless, invisible gas. It can be "seen" only as bubbles in water. What is usually called steam is really a fine mist of water droplets.



# Colloids and glasses

*Carved obsidian makes a sharp arrowhead*

**NATURAL GLASS**
Obsidian forms from molten volcanic rock. The rock cools quickly, and the atoms cannot form a regular pattern. Ancient peoples used obsidian for arrowheads like the one above.

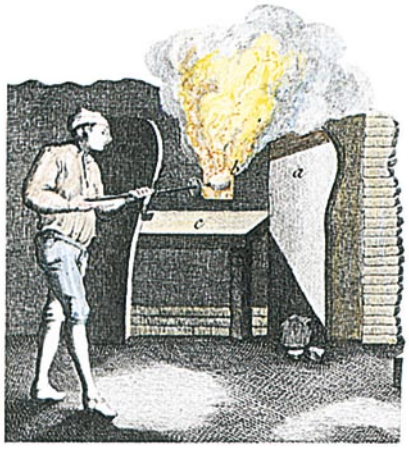
SOME MATTER IS DIFFICULT to classify. For example, lead, a metal, flows like a liquid over centuries. Glass, a seemingly solid substance, is actually a supercool liquid, and flows over decades. The atoms (pp. 34-35) in such substances are not firmly locked into a regular pattern. Instead they form a disorderly pattern, and the atoms move around, allowing the substance to flow. In a form of matter called a colloid, one substance is dispersed through another. The dispersed particles are much larger than atoms, but too small to be seen by the naked eye. Colloids include colored glass (solid particles dispersed in a solid), clay (solid in liquid), smoke (solid in gas), milk (liquid in liquid), mist (liquid in gas), and foam (gas in liquid).

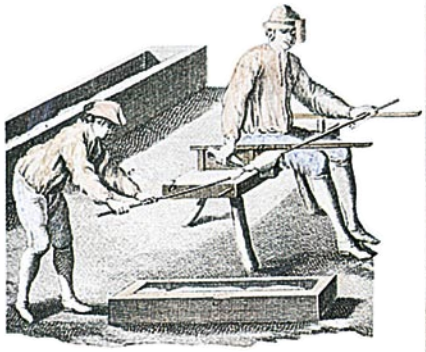

**GLASSBLOWING**
Glass is made by melting sand mixed with other ingredients, and then cooling the liquid rapidly. It was first made around 4000 BC in the Middle East. Glass was blown to fit tightly inside a mold from the 1st century AD. Most glassblowing is now done mechanically, but a traditional method is shown in the following sequence. It is now practiced only for specialized objects.


**1 A GLASS RECIPE**
The main ingredient in the recipe for glass, called the batch, is sand. The next main ingredient is usually soda ash (sodium carbonate), which makes a glass that is fairly easy to melt. Limestone may be used to produce a water-resistant glass.

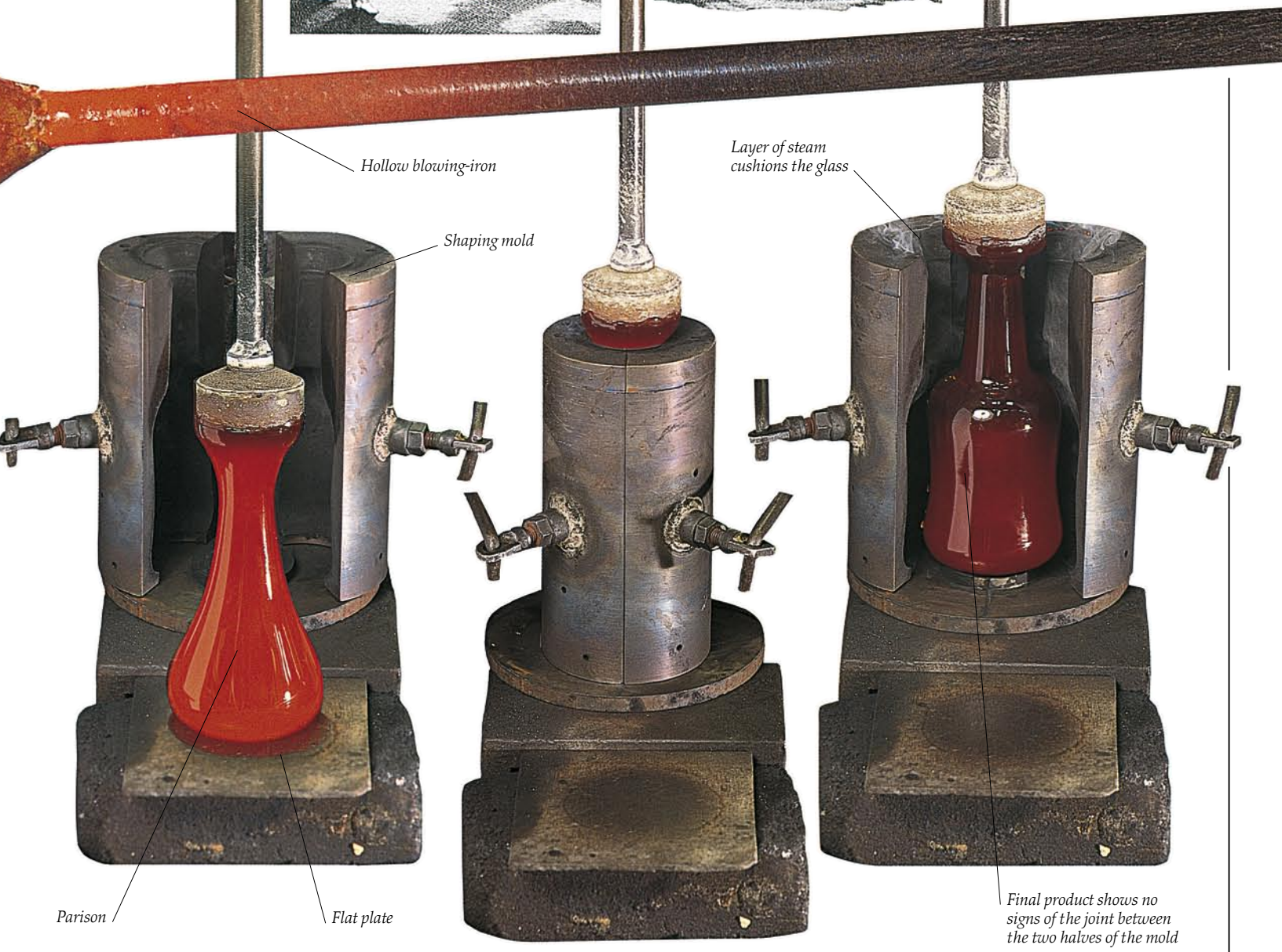
**2 CUTTING GLASS**
A large quantity of the molten glass is gathered on the end of an iron rod by the glassmaker. It is allowed to fall into a measuring mold, and the correct quantity is cut off, using a pair of shears. There are several other traditional glassmaking techniques. Flat glass for windows can be produced by spinning a hot molten blob of glass on the end of a rod. It is spread into a large disc, from which flat pieces can be cut. Glass with a decorated surface can be made by pressing molten glass into a mold.

**A GOOD TURN**
This 18th-century glassmaker is remelting and turning the rim of a glass before correcting its shape. Glass gradually becomes softer over a range of temperatures. In its semi-solid state, glass can easily be shaped into the desired form.





**GAFFER AND SERVITOR**
The gaffer, or master glassmaker, is making a thin stem for a drinking-glass. He rolls the iron rod on the arms of his chair, to keep the glass symmetrical. The servitor, or assistant, draws out one end of the glass with a rod, while the gaffer shapes and cuts the stem.

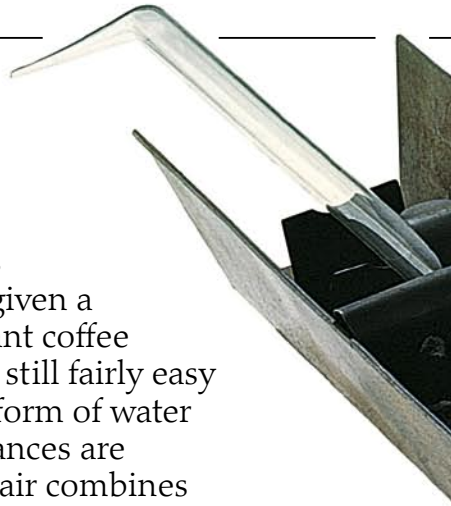



**3 MAKING THE PARISON**
The correct quantity of molten glass is picked up from the measuring mold on a hollow blowing-iron and is reheated in a furnace. The glassmaker blows a little air through the blowing-iron and taps the glass on a flat plate a few times to shape it. The glass is now approximately the size and shape of the finished product – in this case a bottle – and is called a parison. Behind the parison is the open shaping mold, which is bottle-shaped. The parison is now ready to be placed inside.

**4 BLOWING, MOULDING, AND SPINNING**
When the mold has been tightly closed, the glass is gently blown again. The glass expands and takes the shape of the inside of the mold. As well as blowing, the glassblower also spins the blowing-iron rapidly. This ensures that the final object does not show any signs of the joint between the two halves of the mold, or any other defects. The glass never comes in direct contact with the material of the mold. This is because the inside of the mold is wet and a layer of steam forms, cushioning the glass.

**5 ONE BROWN BOTTLE**
The shaping mold is opened to reveal the final product – a reproduction of a 17th-century bottle. This specialized object has to be broken away from the blowing-iron. The jagged mouth of the bottle has to be finished off by reheating it in a furnace and using shaping tools. Since the glass has cooled slightly, the rich brown color provided by the special ingredients in the batch is revealed. In the very early days of glass, it was always colored. The first clear glass was made in the 1st century BC.

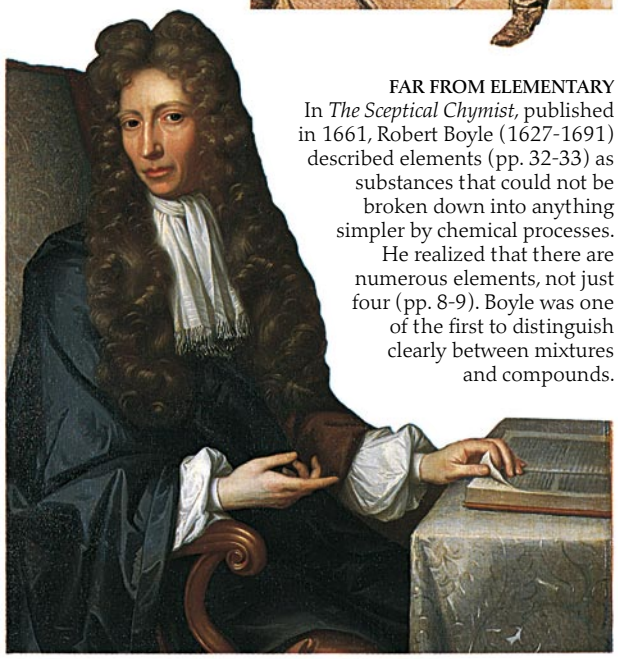
# Mixtures and compounds



WHEN SALT AND SAND ARE MIXED TOGETHER, the individual grains of both substances can still be seen. This loose combination of substances is called a mixture. The mixture of salt and sand is easy to separate – if it is given a gentle shake, the heavier grains of sand settle to the bottom. Mixing instant coffee and hot water produces a closer combination, called a solution. Yet this is still fairly easy to separate. If the solution is gently heated, pure water is given off in the form of water vapor, while solid coffee is left behind. The closest combinations of substances are chemical. When carbon (in the form of charcoal) burns, oxygen from the air combines with it to form the gases carbon dioxide and carbon monoxide. These gases are difficult to break down, and are called compounds.

**WHEAT FROM CHAFF**
Traditionally, wheat was threshed to loosen the edible grains from the chaff (the husks). The grains and chaff formed a mixture that could be separated by "winnowing." Grains were thrown into the air and the breeze blew away the lighter chaff, while the grain fell back.

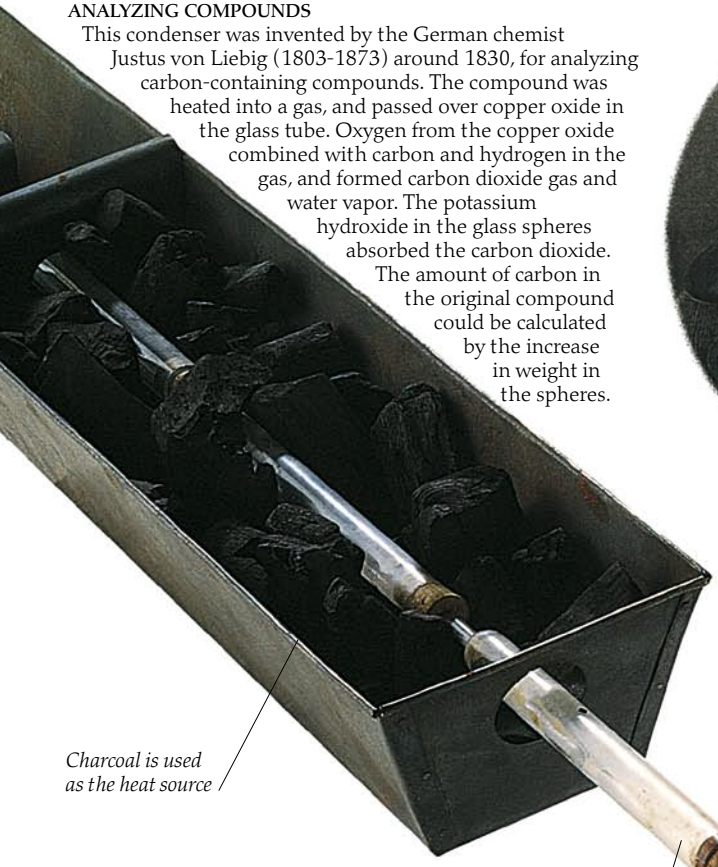
**GOLD IN THE PAN**
Gold prospectors have "panned" for gold since the 19th century. They swill gravel from a streambed around a pan with a little water. Any gold nuggets present separate from the stones because of their high density.



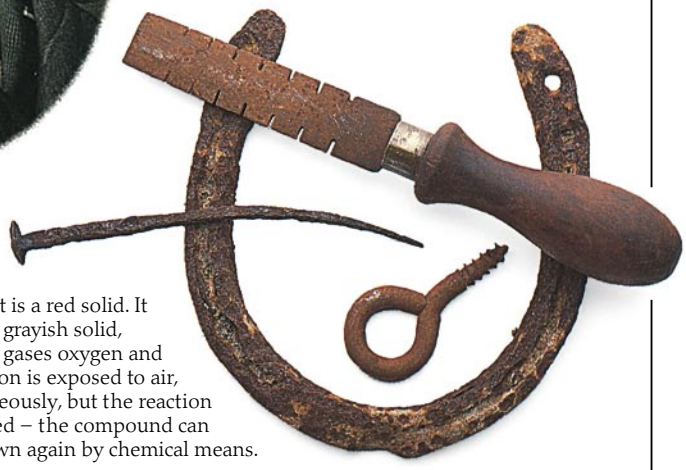
**FAR FROM ELEMENTARY**
In *The Sceptical Chymist*, published in 1661, Robert Boyle (1627-1691) described elements (pp. 32-33) as substances that could not be broken down into anything simpler by chemical processes. He realized that there are numerous elements, not just four (pp. 8-9). Boyle was one of the first to distinguish clearly between mixtures and compounds.

**COLORFUL REPORT**
Mixtures of liquids or gases can be separated by chromatography. The blotting paper shown here has been dipped into an extract of flower petals. Some of the liquid is drawn up into the paper, but the components flow at different rates, and separate out into bands of colors.

**ANALYZING COMPOUNDS**
This condenser was invented by the German chemist Justus von Liebig (1803-1873) around 1830, for analyzing carbon-containing compounds. The compound was heated into a gas, and passed over copper oxide in the glass tube. Oxygen from the copper oxide combined with carbon and hydrogen in the gas, and formed carbon dioxide gas and water vapor. The potassium hydroxide in the glass spheres absorbed the carbon dioxide. The amount of carbon in the original compound could be calculated by the increase in weight in the spheres.



**REFLECTIVE THINKER**
Justus von Liebig made many advances in the chemistry of "organic" substances. This originally meant substances made in living organisms, but now refers to most carbon-containing substances (pp. 40-43). His scientific feats included devising standard procedures for the chemical analysis of organic compounds, inventing a method of making mirrors by depositing a film of silver on glass, pioneering artificial fertilizers, and founding the first modern teaching laboratory in chemistry.



**RUSTING AWAY**
The compound rust is a red solid. It forms when iron, a grayish solid, combines with the gases oxygen and hydrogen. When iron is exposed to air, rust forms spontaneously, but the reaction is not easily reversed – the compound can only be broken down again by chemical means.

*Charcoal is used as the heat source*

*Glass tube contains copper oxide*

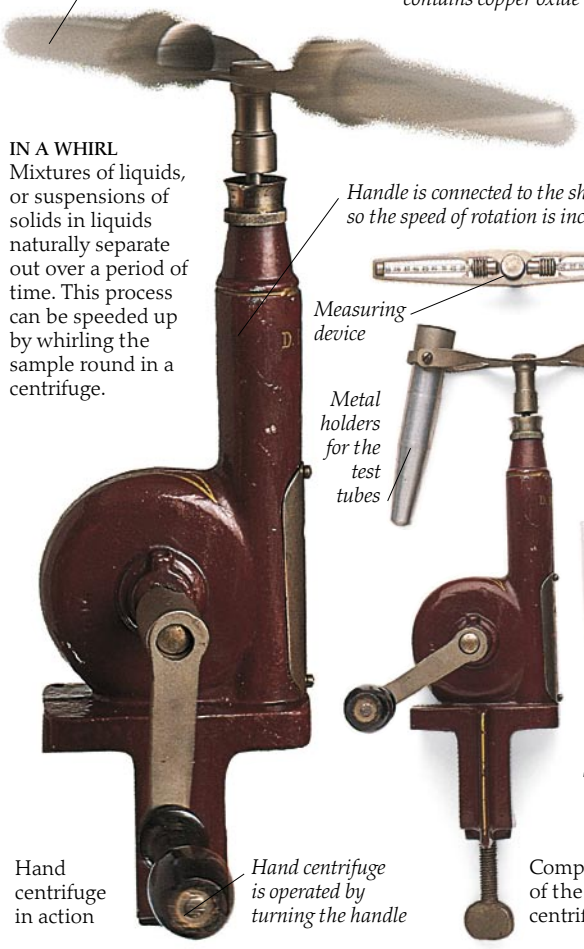
**SALT OF THE EARTH**
In the 19th century salt was shown to be a compound of two previously unknown substances – sodium, a silvery metal, and chlorine, a poisonous gas.

*Potassium hydroxide in the glass spheres absorbs the carbon dioxide*

*Calcium chloride in this tube absorbs water, allowing the amount of hydrogen in the compound to be calculated*

*Sample experiences a strong force*

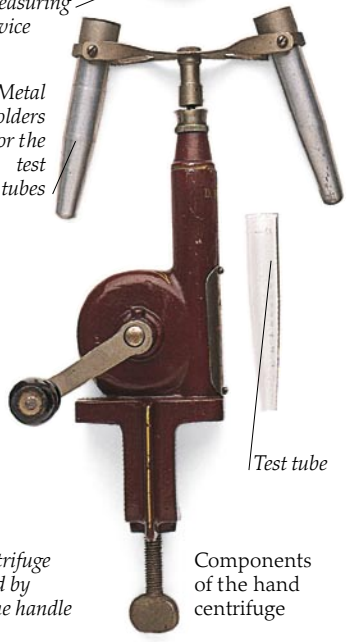
**IN A WHIRL**
Mixtures of liquids, or suspensions of solids in liquids naturally separate out over a period of time. This process can be speeded up by whirling the sample round in a centrifuge.



*Handle is connected to the shaft by gears so the speed of rotation is increased*

*Measuring device*

*Metal holders for the test tubes*



*Test tube*

Hand centrifuge in action

*Hand centrifuge is operated by turning the handle*

Components of the hand centrifuge

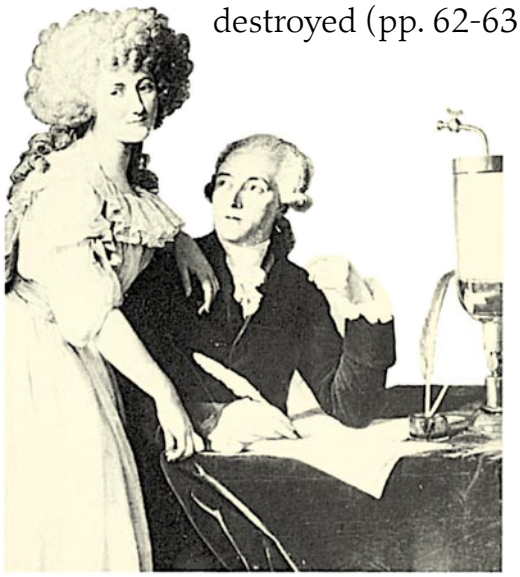


**SALT OF THE SEA**
These salt pans in India are shallow pits that are flooded with seawater (a mixture of salt and water). The water evaporates in the hot sunshine, but only pure water comes off as a vapor. The salt is left behind as a white solid.

# Conservation of matter

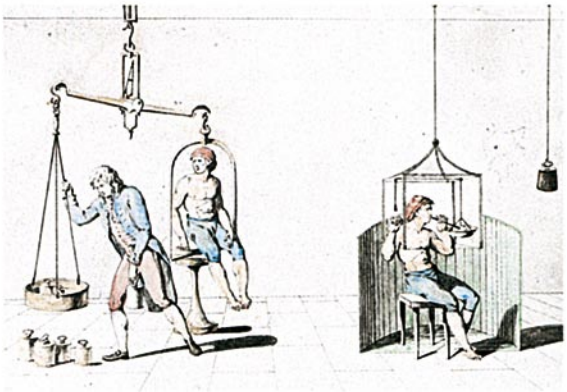
**GREAT SURVIVOR**
The original matter in a long-dead organism is dispersed and survives. A fossil is the last visible trace of an organism.

MATTER COMBINES, separates, and alters in countless ways. During these changes, matter often seems to appear and disappear. Hard deposits of scale build up in a kettle. Water standing in a pot dries up. Plants grow, and their increase in weight is much greater than the weight of the water and food that they absorb. In all everyday circumstances matter is conserved – it is never destroyed or created. The scale found in the kettle built up from dissolved matter that was present in the water all the time. The water in the pot turned into unseen gases that mingled with the air. The increased bulk of the plants came from the invisible carbon dioxide gas in the air. Only in nuclear explosions, or in the sun and stars, or in other extreme situations, can matter be created or destroyed (pp. 62-63).



**A COUPLE OF CHEMISTS**
Antoine Lavoisier (1743-1794) stated the principle of conservation of matter in 1789. This was not a new idea – matter had been assumed to be everlasting by many previous thinkers. Lavoisier, however, was the first to demonstrate this principle actively. His wide-ranging investigations were renowned for their rigor – he carried out experiments that were conducted in sealed vessels, and made accurate records of the many substances involved in chemical reactions. This work was extremely careful and laborious, but he was aided by another talented chemist and devoted coworker, his wife, Marie-Anne.

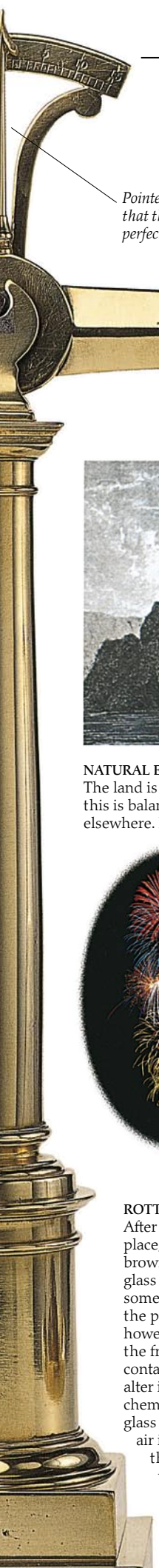

Ornamental pan scales



**THE BALANCE OF LIFE**
Lavoisier weighed people and animals over long periods of time to discover what happened to their air, food, and drink. He calculated the quantities of gases involved by examining the measured quantities of solids and liquids that they had consumed.

**WEIGHTY MATTER**
In the late 18th century the balance became the chemist's most important measuring instrument. Accurate weighing was the key to keeping track of all the matter involved in a reaction. It led to the abandonment of the phlogiston theory (pp. 30-31) – that when a material burns, a substance called phlogiston is always released.

**WEIGHING THE EVIDENCE**
Lavoisier's theory of the conservation of matter can be effectively demonstrated by comparing the weight of substances before and after an experiment. Here, a pear is placed under an airtight container and weighed. The pear is left for a few days and then weighed again. The two weights can be compared to discover whether the process of decay has involved any overall weight change.

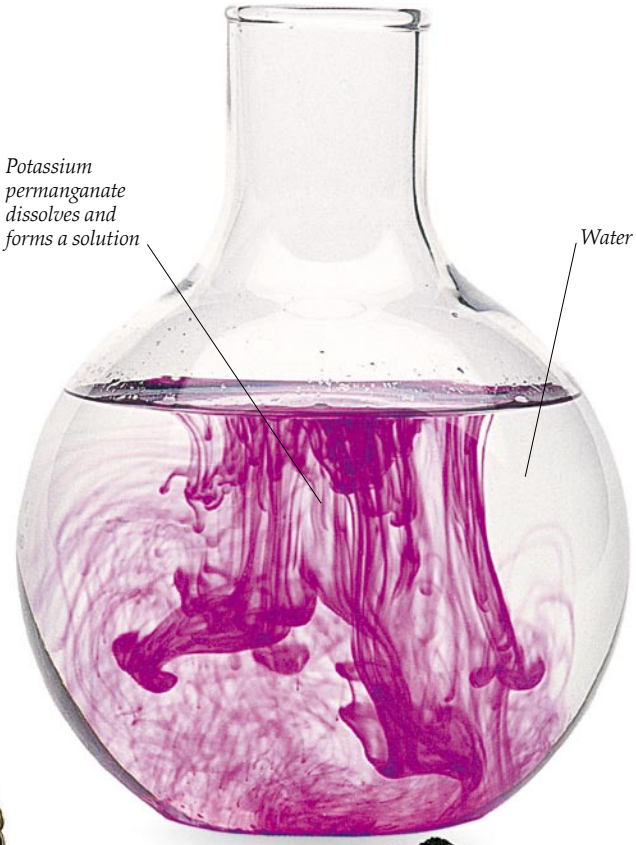


*Pointer indicates that the pans are perfectly balanced*

**NATURAL EROSION**
The land is constantly worn away by wind, rain, and waves, yet this is balanced by the natural building up of new land forms elsewhere. No matter is lost or gained overall.

**OUT WITH A BANG**
When fireworks go off, gunpowder burns, as well as other chemicals, plus the cardboard and paper of the firework packaging. The burning products form gases and a small quantity of solids. Though widely scattered, the combined products weigh the same as the original.


**ROTTEN RESULT**
After a few days, rotting begins to take place, and some parts of the pear become brown and mushy. In the air under the glass dome there is now less oxygen, for some of it combines with the substances in the pear. There is more carbon dioxide, however, as well as other gases released by the fruit. Overall, the weight of the container plus its contents does not alter in the slightest degree. Early chemists did not realize that if the glass dome is lifted before weighing, air is likely to enter or escape, and therefore affect the weight of the container and its contents.

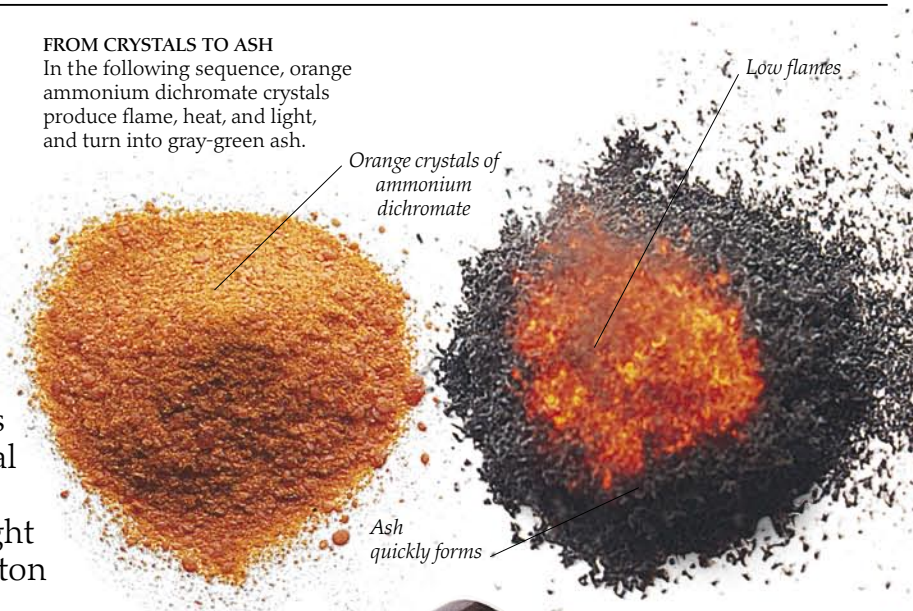




**AN OBVIOUS SOLUTION**
Solids left in water often dissolve. If the solids are colorless, such as salt, it is easy to believe they have disappeared completely. In fact they have just thoroughly mixed, and broken into minute particles, which have spread through the liquid. When the solid is colored, like this potassium permanganate, it is easier to believe that it still exists in the liquid. Weighing the solution confirms that it weighs the same as the original liquid and solid.

# Burning matter

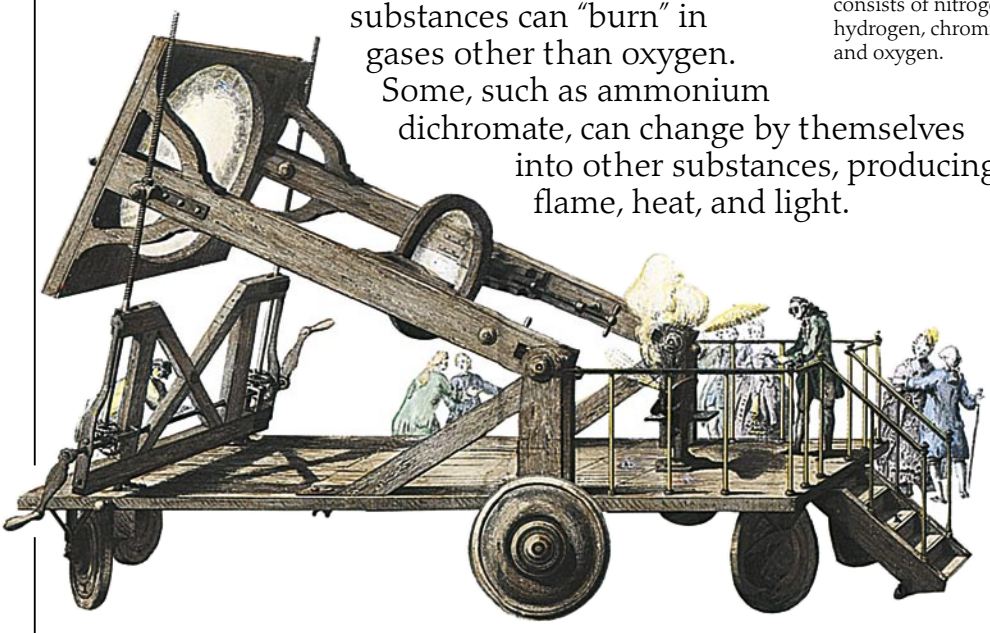
**FROM CRYSTALS TO ASH**
In the following sequence, orange ammonium dichromate crystals produce flame, heat, and light, and turn into gray-green ash.




**1 READY TO REACT** Ammonium dichromate is a substance used in indoor fireworks. It consists of nitrogen, hydrogen, chromium, and oxygen.

**2 VITAL SPARK** When lit by a flame, the substance's atoms (pp. 34-35) form simpler substances, and produce heat and light.

ONE OF THE FIRST great achievements of 18th-century science was the explanation of burning (also known as combustion). Georg Stahl (1660-1734) put forward the theory that an element, phlogiston, was given out in burning. His theory was wrong – it would mean that all substances would lose weight when they burn. Several chemists had already observed that some substances such as metals increase in weight during burning, and the theory of phlogiston was firmly denied by Antoine Lavoisier (pp. 28-29). He argued that air contains a gas that combines with a substance when it burns, and he named the gas oxygen. Sometimes substances can "burn" in gases other than oxygen. Some, such as ammonium dichromate, can change by themselves into other substances, producing flame, heat, and light.



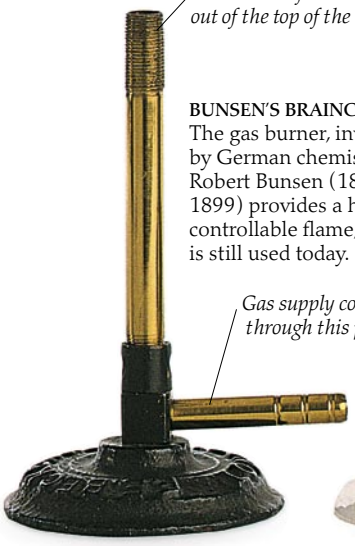
**THE HEAT OF THE MOMENT**
Antoine Lavoisier was particularly interested in chemical reactions that required great heat. One problem in his scientific work was to obtain heat that was both intense and "clean," for often the reacting substances were contaminated by smoke and soot from the heat source (usually a flame). His solution was this giant mobile burning-glass, or convex lens, with which he enthralled the French populace in 1774.


**FOCUS OF ACTIVITY**
Heat brings about many changes in matter. It can cause different substances to react together, or it can make a reaction go faster. Here the heat is produced as sunlight is focused by a large convex lens to fall on to a flask containing ice. This causes the ice to melt – a physical rather than a chemical change. If sunlight is focused on to paper, the paper can smolder, and even burst into flame. This is a chemical change, and is an example of combustion.


**3 BREAKDOWN**
The substance is rapidly converted into chromium oxide, a compound of chromium and oxygen, and into nitrogen and water vapor, both invisible gases.

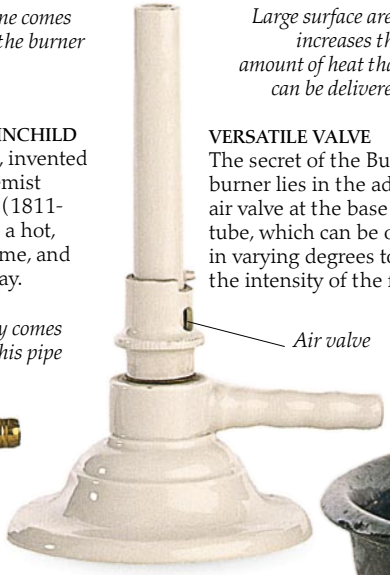
**4 ASHEN ENDING**
The orange crystals of ammonium dichromate have broken down, leaving a large pile of chromium oxide. The nitrogen and water vapor have escaped into the air.


**A CHEMIST'S BLOWPIPES**
These 19th-century blowpipes enabled a chemist to direct a thin jet of air accurately on to substances being heated in a flame. This produced intense heat at one spot.



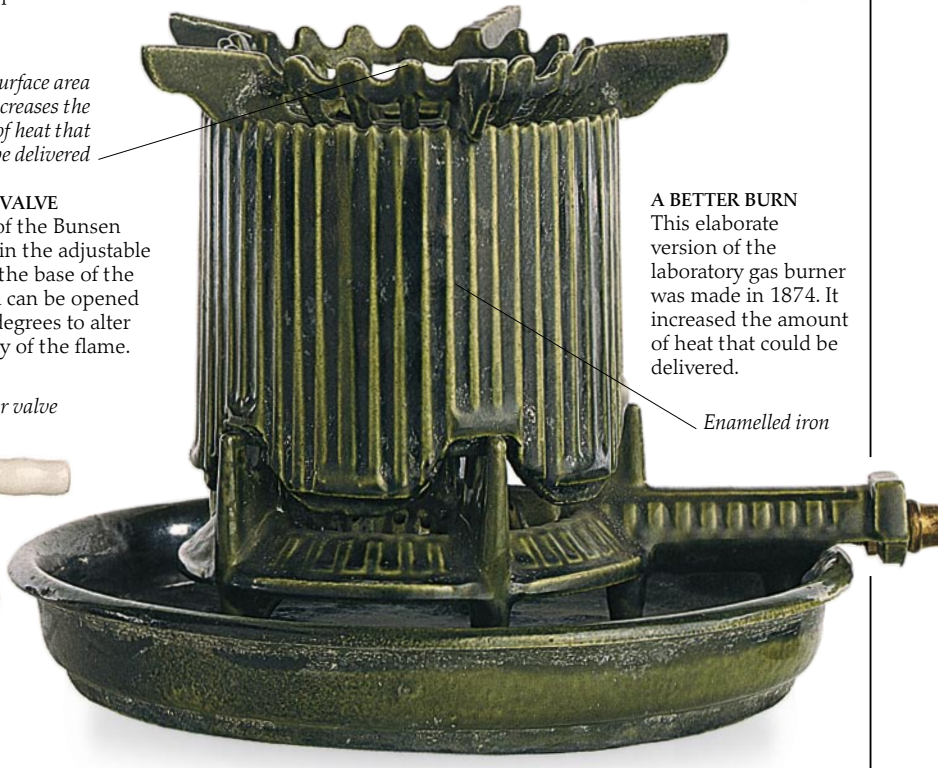

**BUNSEN'S BRAINCHILD**
The gas burner, invented by German chemist Robert Bunsen (1811-1899) provides a hot, controllable flame, and is still used today.

Bunsen burner from 1889




**VERSATILE VALVE**
The secret of the Bunsen burner lies in the adjustable air valve at the base of the tube, which can be opened in varying degrees to alter the intensity of the flame.

Bunsen burner made from flame resistant porcelain




**A BETTER BURN**
This elaborate version of the laboratory gas burner was made in 1874. It increased the amount of heat that could be delivered.

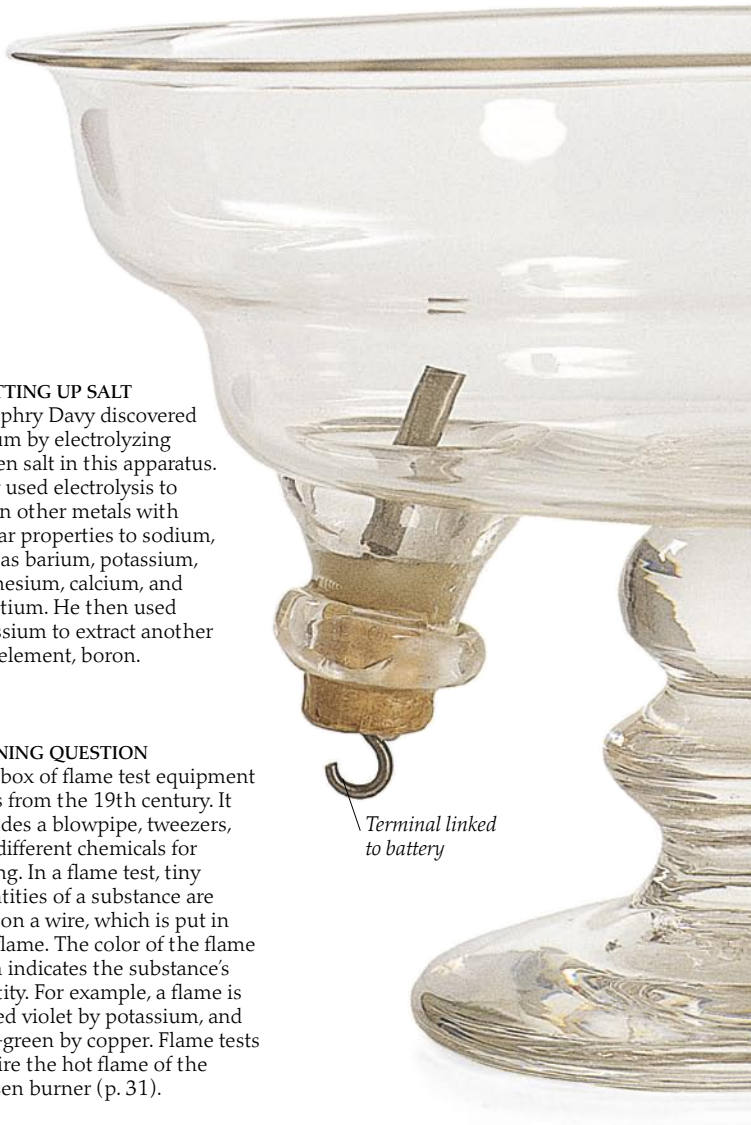
# Charting the elements

**FLAME TEST**
Here common salt (sodium chloride) burns yellow in a flame, revealing the presence of the element sodium.

ELEMENTS ARE PURE SUBSTANCES – they do not contain anything else, and cannot be broken down into simpler substances. Many of the elements were discovered during the 18th and 19th centuries, particularly by using processes such as electrolysis and spectroscopy. In electrolysis, an electric current is passed through compounds to break them down (pp. 50-51). In spectroscopy, the light given out by hot substances is analyzed with a spectroscope (pp. 56-57) to show an element's characteristic pattern of colors. Dmitri Mendeleyev (1834-1907) brought order to the elements with his "periodic table," based on patterns in properties of elements such as their reactivity.

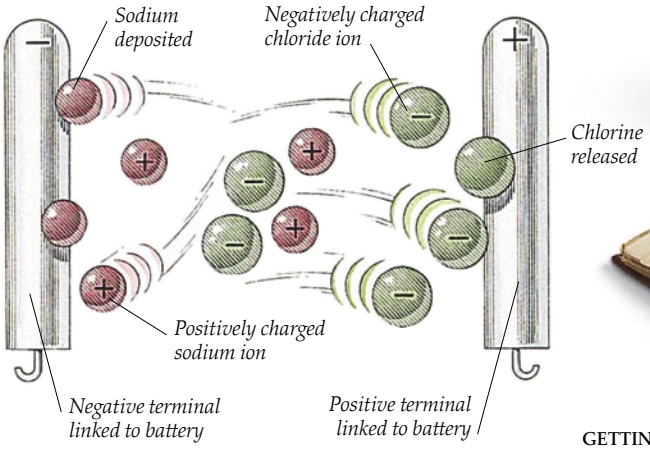
**A BATTERY OF DISCOVERIES**
After learning of Alessandro Volta's invention of the electric battery in 1800, Humphry Davy (1778-1829) built his own. It was large, and had 250 metal plates. He used it for electrolysis, and prepared pure samples of new metals.


**BURNING QUESTION**
This box of flame test equipment dates from the 19th century. It includes a blowpipe, tweezers, and different chemicals for testing. In a flame test, tiny quantities of a substance are held on a wire, which is put in to a flame. The color of the flame often indicates the substance's identity. For example, a flame is turned violet by potassium, and blue-green by copper. Flame tests require the hot flame of the Bunsen burner (p. 31).




**SPLITTING UP SALT**
Humphry Davy discovered sodium by electrolyzing molten salt in this apparatus. Davy used electrolysis to obtain other metals with similar properties to sodium, such as barium, potassium, magnesium, calcium, and strontium. He then used potassium to extract another new element, boron.

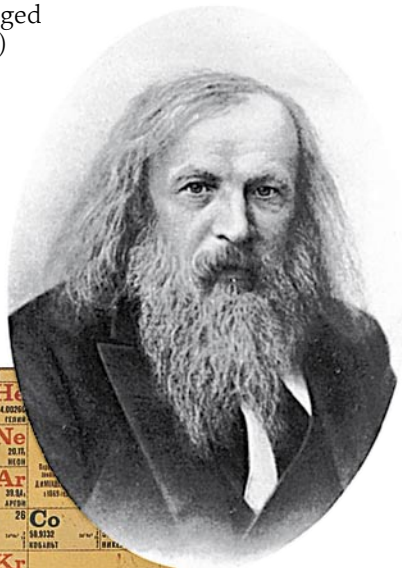
**ELECTRICAL BREAKDOWN**
Common salt consists of sodium and chloride ions – positively charged sodium atoms, and negatively charged chlorine atoms (pp. 50-51). When salt is melted, the ions move around each other. If metal plates connected to a battery are placed in the molten salt, the positive plate attracts the chloride ions, and the negative plate attracts the sodium ions.

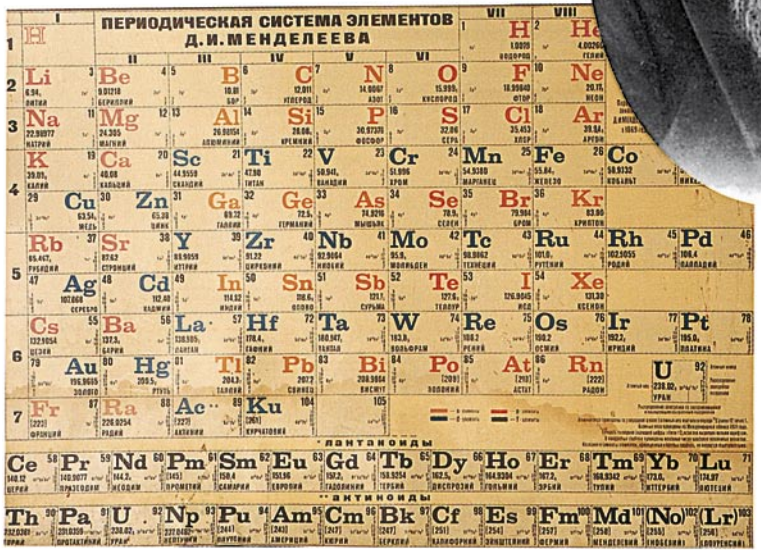



**GETTING THE GREEN LIGHT**
In 1861 William Crookes (p. 48) discovered a new element, thallium, by spectroscopy. His many samples of thallium compounds are shown here, with one of his notebooks detailing the discovery. He could detect minute quantities of the new element because it emits a brilliant green light when in a hot flame.


# The periodic table

The properties of the elements can be described and understood in terms of the periodic table. It shows more than 100 elements, arranged vertically into columns (called groups) and horizontally into rows (called periods). Properties change systematically going down each group and along each period, but elements in each group have generally similar properties. For example, group VIII contains the very unreactive "noble" gases such as argon (Ar), while group I contains very reactive metals such as sodium (Na).

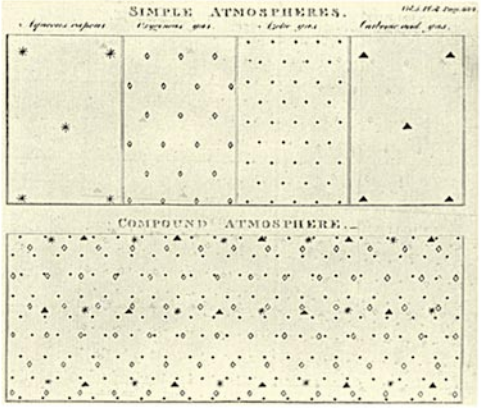





**PATTERN FINDER**
Dmitri Mendeleyev's periodic table suggested corrections to previously accepted chemical data, and successfully predicted the existence of new elements. The Russian periodic table shown here is based on Mendeleyev's original of 1869.

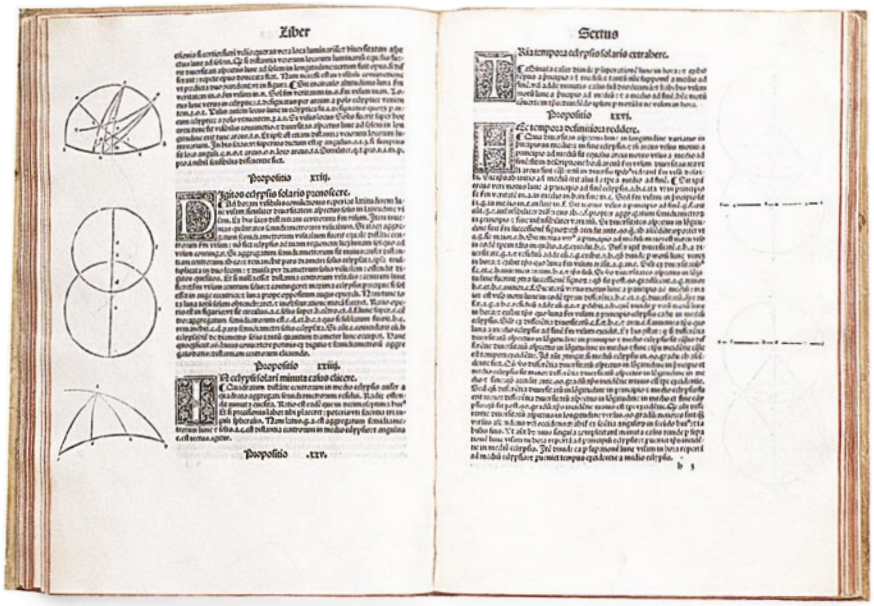
# The building blocks

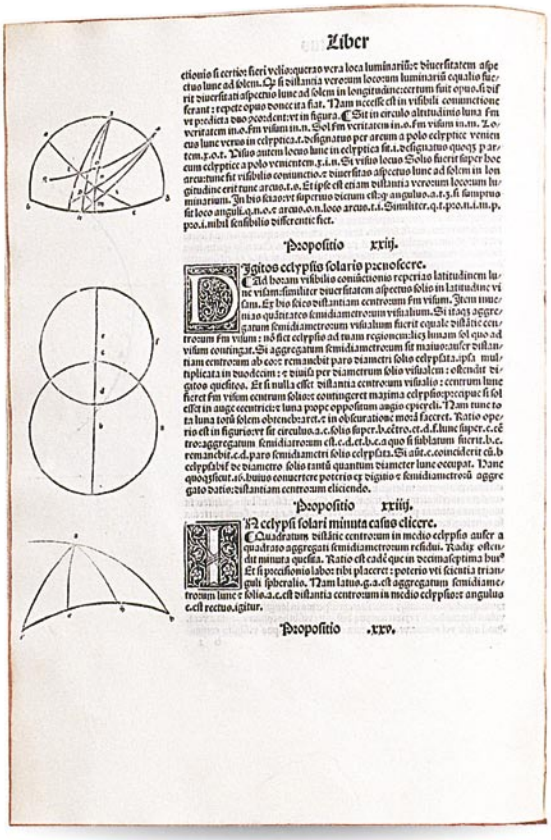
As scientists discovered more elements, they pondered over the ultimate nature of matter. The ancient idea of atoms (pp. 8-9) received a boost from English chemist John Dalton (1766-1844) in 1808. He proposed that each element has its own unique atom, and that each compound is formed by a certain combination of atoms. He showed that the weights of atoms relative to each other could be found by weighing the elements that combined in particular compounds. The comparative weight of an atom could be found, but not the actual weight – a given atom could only be said to be so many times heavier than, for example, one of hydrogen, the lightest atom.




ATMOSPHERIC ATOMS
John Dalton drew these diagrams in 1802. He was an enthusiastic meteorologist and knew that air consists of oxygen, water vapor, carbon dioxide, and nitrogen (top diagram). He developed his atomic theory while explaining why these gases remain mixed, rather than forming separate layers.

CLOSING IN ON ATOMS
Atoms make up the world in much the same way that the letters of the alphabet make up a book. Scientists need a close-up view to study atoms, just as readers have to peer closely at a page to study individual letters.

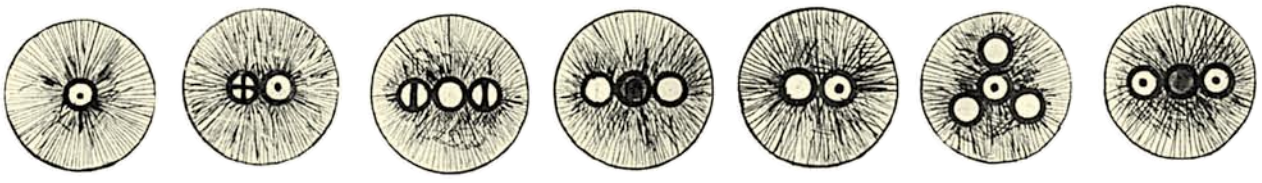



1 THE BOOK OF THE WORLD
A glance at any book shows that it is made up of many things, such as pictures, text of large and small print, and different chapters. Similarly, a glance at the "book of the world" shows that it is a kaleidoscopic array of many sorts of chemical substances. But such a glance does not reveal whether or not the world is made of atoms.

2 A PAGE AT A TIME
If a reader concentrates on one page of the "book of the world" and temporarily ignores the rest of the pages, this still gives a sample of the world that is very large compared with the atom. Similarly, when studying matter scientifically a small part must be isolated, for example, by examining a substance in a flask in a laboratory. To obtain a more detailed view of matter, scientists need to use instruments.

ELASTIC FLUIDS
Dalton assumed that gases are made of atoms which are far apart and can move independently. This is why gases can be compressed and expanded. He called gases "elastic fluids," and pictured their atoms like these circles.

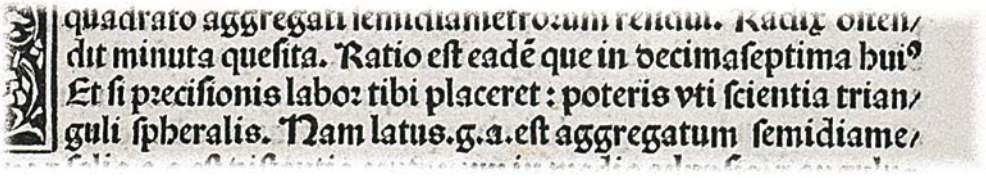


Propositio xxiiij.

In eclypsi solari minuta casus elicere.

Quadratum distãtie centrorum in medio eclypsis auser a quadrato aggregati semidiametrorum residui. Radix ostendit minuta quesita. Ratio est eadẽ que in decimaseptima hui⁹ Et si precisionis labor tibi placeret: poteris vti scientia trianguli spheralis. Nam latus.g.a.est aggregatum semidiametrorum lune ⁊ solis.a.e.est distantia centrorum in medio eclypsis:⁊ angulus e.est rectus.igitur.

3 ENDLESS VARIETY
In close-up, one piece of text consists of many different words. Similarly, with the aid of chemical analysis and instruments, matter can be seen to be made up of an enormous number of different substances.

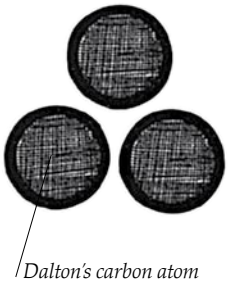


quadrato aggregati semidiametrorum residui. Radix ostendit minuta quesita. Ratio est eadẽ que in decimaseptima hui⁹ Et si precisionis labor tibi placeret: poteris vti scientia trianguli spheralis. Nam latus.g.a.est aggregatum semidiame/

4 NARROW VIEW
A microscope can give a detailed view of a small sample of matter, but this sample may be composed of a variety of substances. It is similar to a sentence, which is made up of many different words.

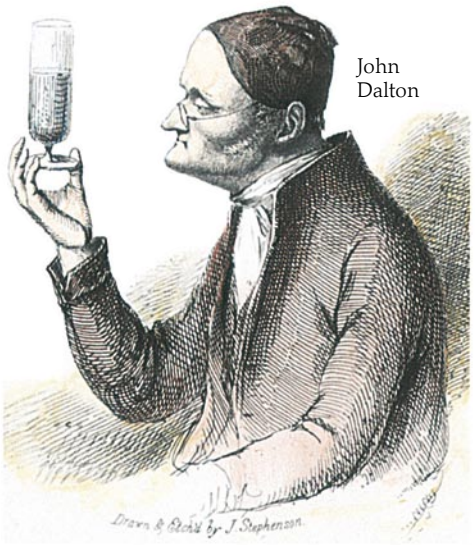
Ratio

5 WORDS OF SUBSTANCE
"Words" in the "book of the world" are groups of atoms, or molecules (pp. 36-37). Here, the 26 letters of the Roman alphabet make up words. About 90 different kinds of atom make up molecules.



*Dalton's carbon atom*

6 SINGULAR CHARACTERS
The letters on the printed page correspond to atoms. Just as letters group into words, so atoms form molecules. There is no limit to the words that can be formed from the alphabet, and any number of compounds can be formed from atoms. Not all possible combinations of letters are permitted, and neither are all combinations of atoms.



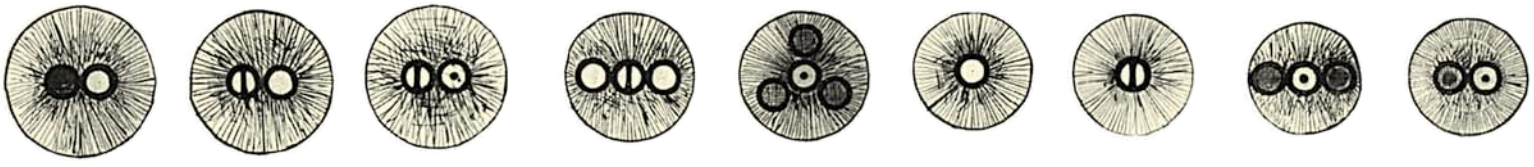
John Dalton

DALTON'S ATOMS AND ELEMENTS
In 1808 John Dalton published his atomic theory. It suggested that all matter is made up of indivisible atoms; each element is composed of atoms of characteristic weight; and compounds are formed when atoms of various elements combine in definite proportions. Below are Dalton's symbols for the atoms of the 36 elements that he believed to exist (over 100 elements have now been found). Some of Dalton's elements shown here, for example lime and soda, are actually compounds, not elements. Dalton also calculated the weight of each element's atom, by comparing it to hydrogen.

ELEMENTS

| | Wt | | Wt |
|---|---|---|---|
| Hydrogen | 1 | Strontian | 46 |
| Azote | 5 | Barytes | 68 |
| Carbon | 5½ | Iron | 50 |
| Oxygen | 7 | Zinc | 56 |
| Phosphorus | 9 | Copper | 56 |
| Sulphur | 13 | Lead | 90 |
| Magnesia | 20 | Silver | 190 |
| Lime | 24 | Gold | 190 |
| Soda | 28 | Platina | 190 |
| Potash | 42 | Mercury | 167 |

Dalton's elements

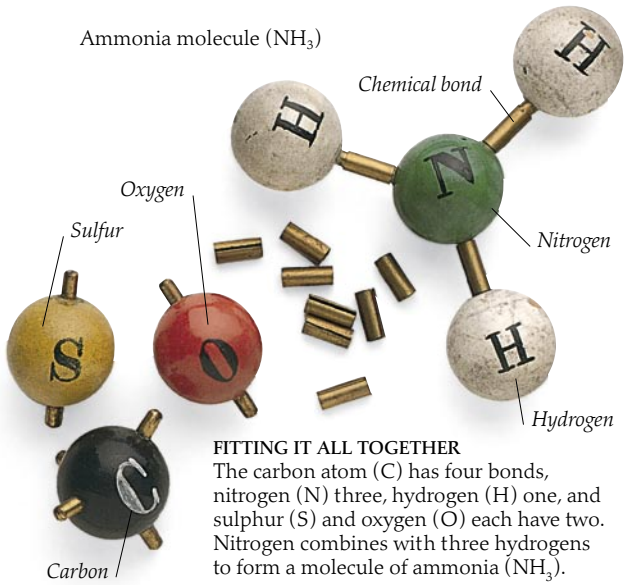


19th-century molecular model of monochloromethane, a type of solvent

# Molecules

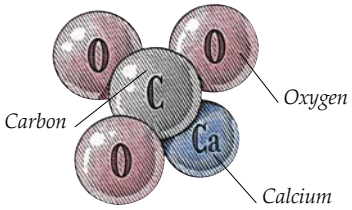
ATOMS CAN EXIST SINGLY in some gases, but in many substances they form groups called "molecules." For example, the molecule of water consists of an oxygen atom (O) joined to two hydrogen atoms (H). Its chemical formula is $H_2O$. Some molecules can be much bigger than this, containing thousands of atoms. In the mid-19th century it was realized that chemical bonds could explain the ways in which atoms link together to form molecules. A bond is like a hook that can link to a similar hook on another atom. For example, an atom of the gas nitrogen has three hooks, while a hydrogen atom has one. Each bond on the nitrogen atom can link to the bond on one hydrogen atom, which produces the molecule $NH_3$, the gas given off by smelling salts.

Ammonia molecule ($NH_3$)



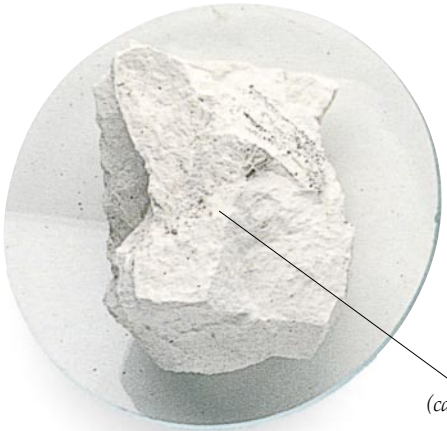

**FITTING IT ALL TOGETHER**
The carbon atom (C) has four bonds, nitrogen (N) three, hydrogen (H) one, and sulphur (S) and oxygen (O) each have two. Nitrogen combines with three hydrogens to form a molecule of ammonia ($NH_3$).

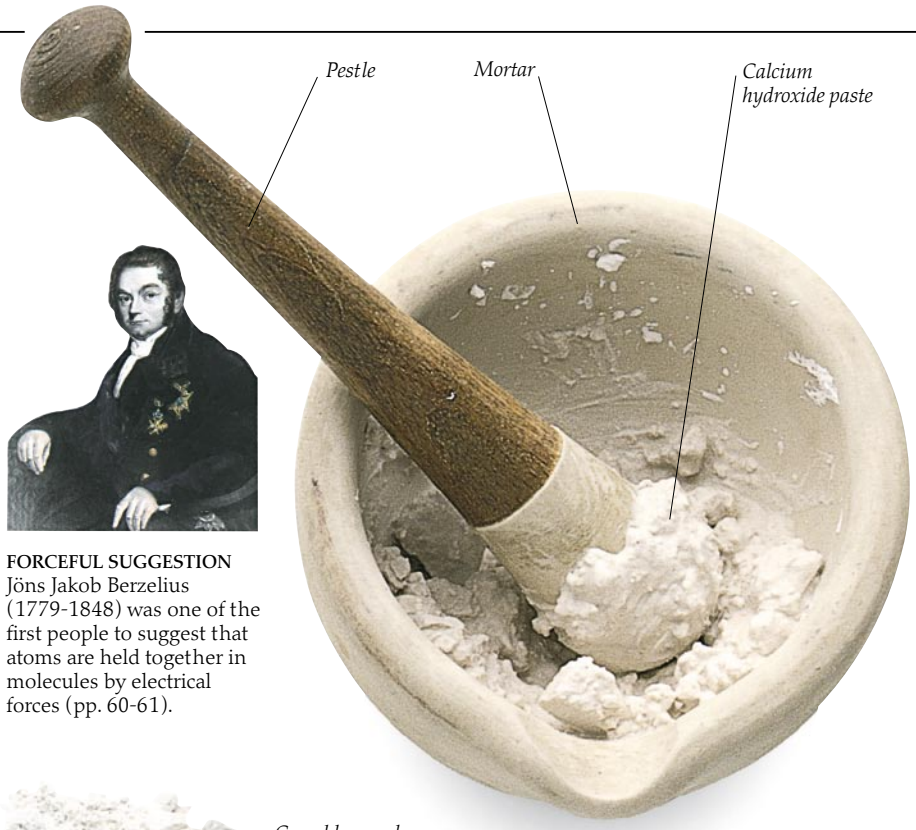
Calcium carbonate molecule ($CaCO_3$)





**1 THE RAW MATERIAL**
Limestone is a whitish rock with the chemical name of calcium carbonate. As this name suggests, the molecule of limestone contains atoms of calcium and carbon, but it also contains oxygen. Each atom of carbon is tightly joined to three of oxygen, and this group is more loosely linked to one atom of calcium.



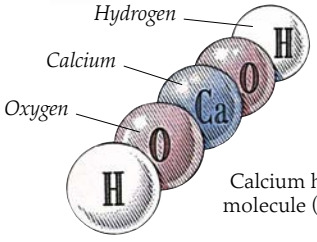





**FORCEFUL SUGGESTION**
Jöns Jakob Berzelius (1779-1848) was one of the first people to suggest that atoms are held together in molecules by electrical forces (pp. 60-61).

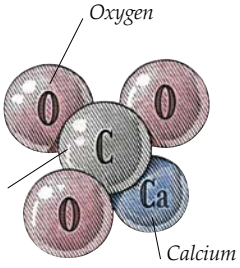
**ITALIAN IDEAS**
Amedeo Avogadro (1776-1856) suggested that in equal volumes of any two gases there are always the same number of molecules, if the gases are at the same temperature and pressure. For about 50 years his idea was largely ignored, until another Italian chemist, Stanislao Cannizzaro (1826-1910), publicized it. The idea was then quickly accepted, and it helped to clarify many chemical reactions.






Calcium hydroxide molecule ($Ca(OH)_2$)

Calcium carbonate molecule ($CaCO_3$)




**3 ADDING WATER**
When water is added to calcium oxide powder there is a strong reaction, and the powder swells up and gives out heat. The molecules of the calcium oxide and of the water, $H_2O$, rearrange themselves to form molecules of calcium hydroxide, a soft and pasty substance. As its name suggests, this molecule contains calcium, hydrogen, and oxygen. Its formula is $Ca(OH)_2$, showing that two oxygen-hydrogen pairs (OH) are joined to a calcium atom.

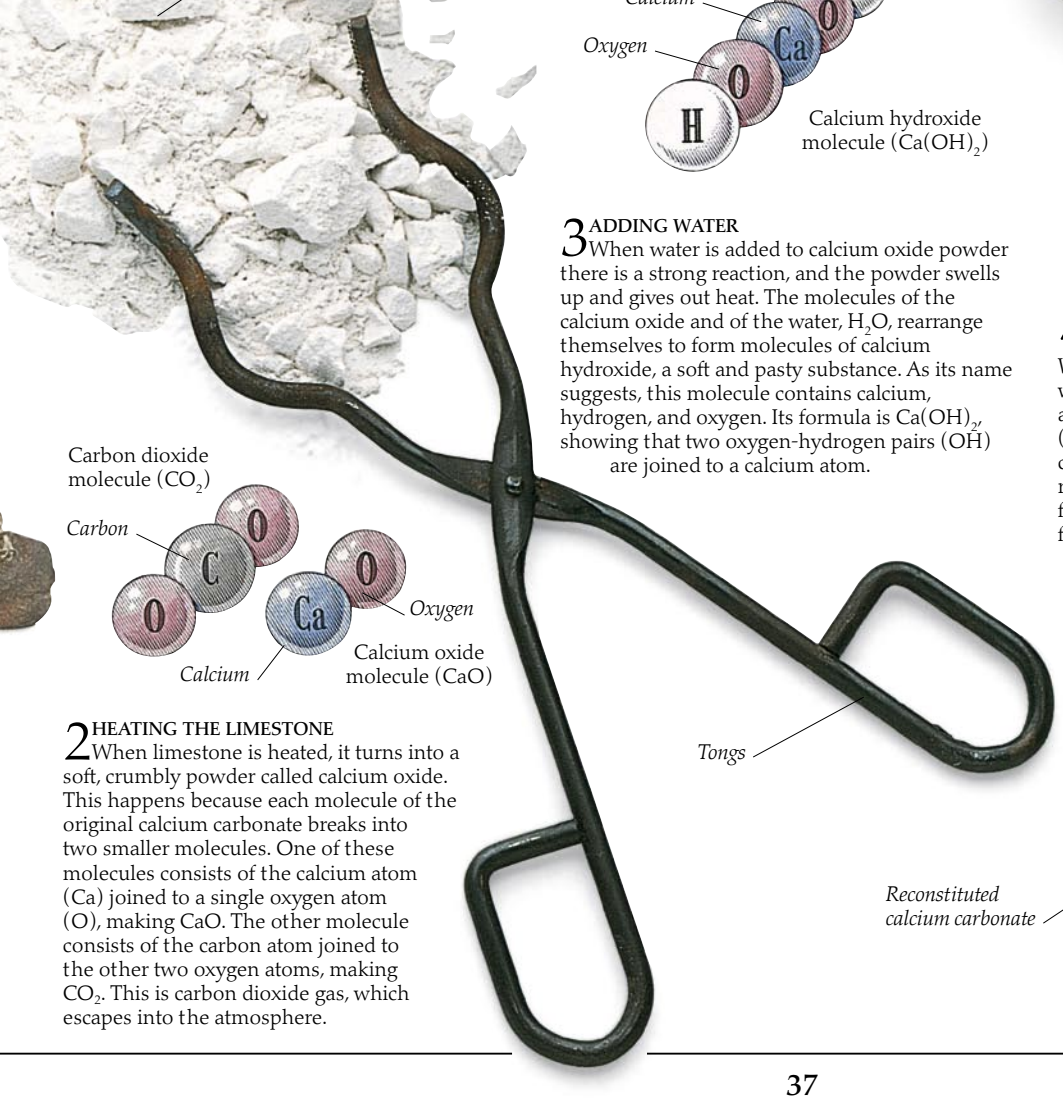
**4 BACK TO CALCIUM CARBONATE**
The calcium hydroxide dries and hardens. Water molecules ($H_2O$) are given off into the air, while carbon dioxide molecules ($CO_2$) from the air are absorbed. The calcium hydroxide ($Ca(OH)_2$) turns into calcium carbonate ($CaCO_3$), chemically identical to the raw material. The reconstituted calcium carbonate looks different from the original limestone because it was not formed under high pressure within the Earth.

Carbon dioxide molecule ($CO_2$)




Calcium oxide molecule (CaO)

**2 HEATING THE LIMESTONE**
When limestone is heated, it turns into a soft, crumbly powder called calcium oxide. This happens because each molecule of the original calcium carbonate breaks into two smaller molecules. One of these molecules consists of the calcium atom (Ca) joined to a single oxygen atom (O), making CaO. The other molecule consists of the carbon atom joined to the other two oxygen atoms, making $CO_2$. This is carbon dioxide gas, which escapes into the atmosphere.



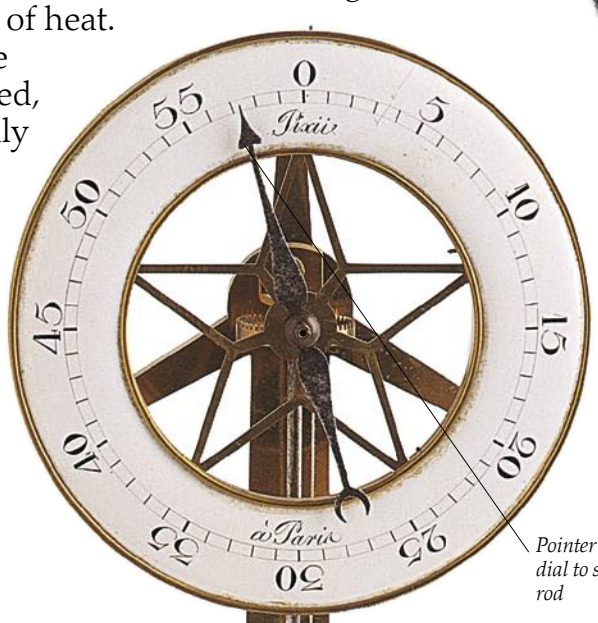

# Molecules in motion

Highly magnified pollen grains – the key to molecular movement

UP UNTIL THE MID-18TH CENTURY, there was a widely accepted theory that heat was a "fluid" called caloric. However, in 1799 Count Benjamin Rumford (1753-1814) observed that limitless quantities of heat could be generated in the boring of cannon barrels. He suggested that the drilling work was increasing the motions of the atoms that made up the metal. This idea gained support when James Joule (1818-1889) did experiments to measure exactly how much work was needed to generate a definite amount of heat.

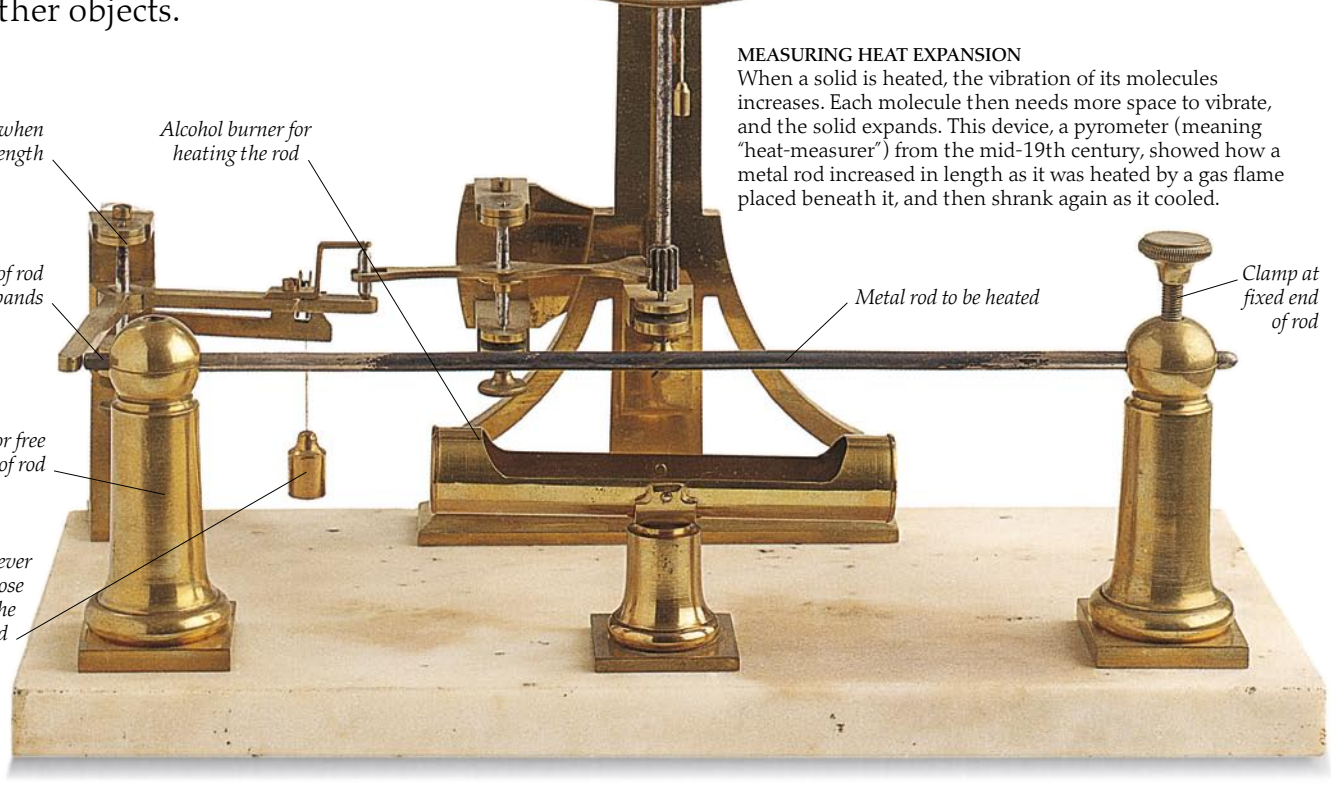
When heat is applied to matter, the motion of the molecules is increased, and the temperature rises. Gradually it was realised that the differences between the three states of matter – solids, liquids, and gases (pp. 22-23) – are caused by the motion of molecules. The molecules in a solid are fixed, but can vibrate. The molecules in a liquid move around, but still remain in contact with each other. In a gas the molecules fly around freely, and move in straight lines until they collide with each other or with other objects.

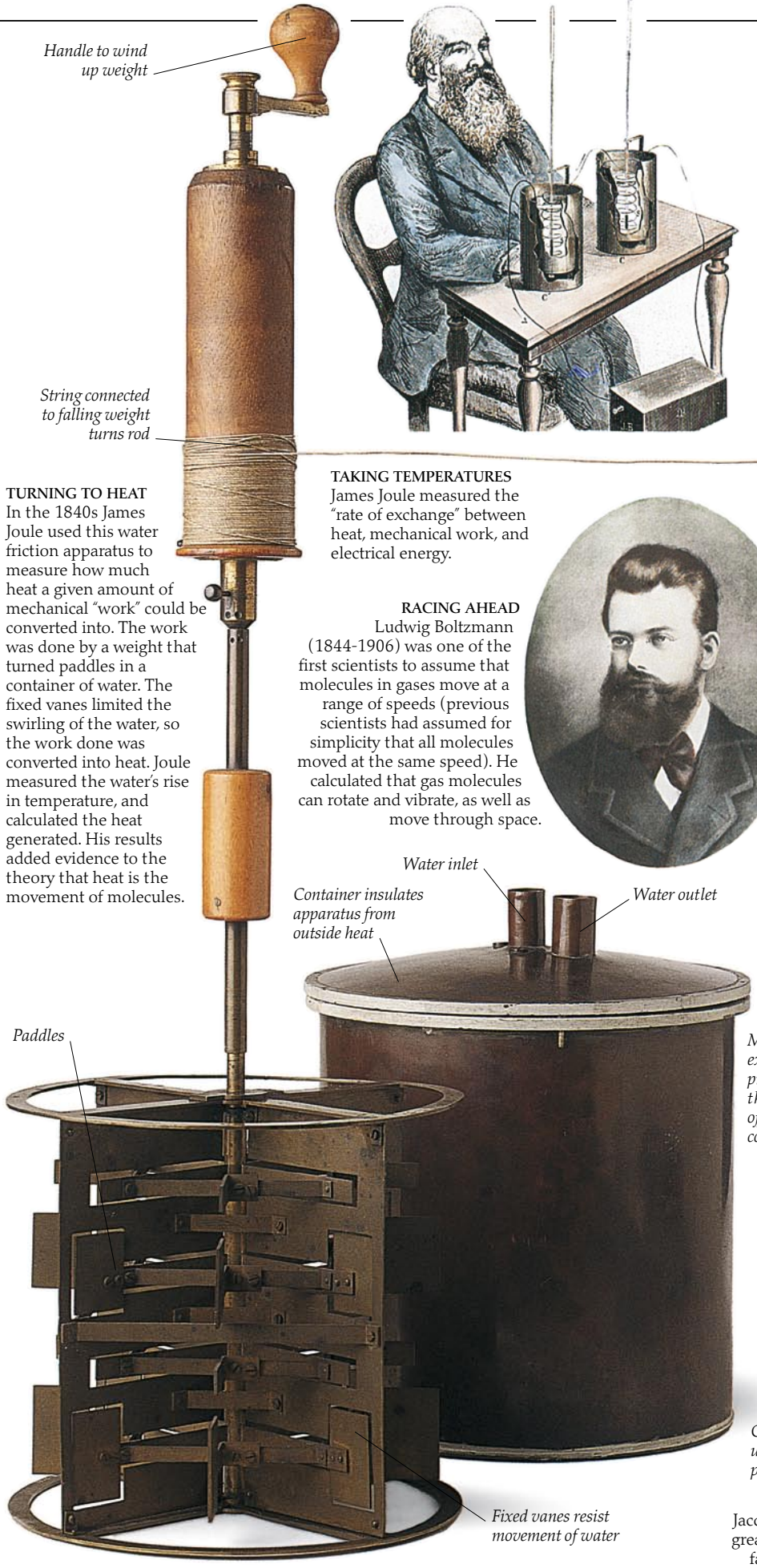
**DANCE OF THE POLLEN**
In 1827, Scotsman Robert Brown (1773-1858) observed pollen grains under a microscope. The grains were suspended in a liquid, and were in constant motion. He thought the motion originated in the pollen particles. But Albert Einstein (p. 55) in 1905, and Jean Perrin (1870-1942) in 1909, explained that the grains were being buffeted by the movement of the molecules in the liquid.




*Pointer moves around the dial to show expansion of the rod*

**MEASURING HEAT EXPANSION**
When a solid is heated, the vibration of its molecules increases. Each molecule then needs more space to vibrate, and the solid expands. This device, a pyrometer (meaning "heat-measurer") from the mid-19th century, showed how a metal rod increased in length as it was heated by a gas flame placed beneath it, and then shrank again as it cooled.





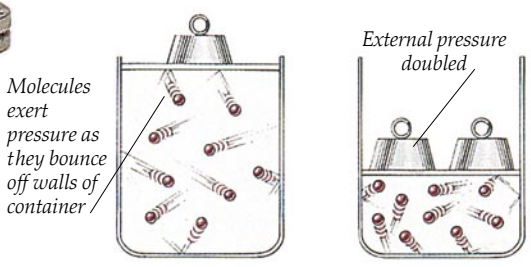

**TURNING TO HEAT**
In the 1840s James Joule used this water friction apparatus to measure how much heat a given amount of mechanical "work" could be converted into. The work was done by a weight that turned paddles in a container of water. The fixed vanes limited the swirling of the water, so the work done was converted into heat. Joule measured the water's rise in temperature, and calculated the heat generated. His results added evidence to the theory that heat is the movement of molecules.



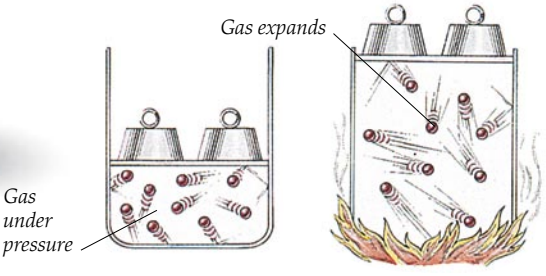
**TAKING TEMPERATURES**
James Joule measured the "rate of exchange" between heat, mechanical work, and electrical energy.

**RACING AHEAD**
Ludwig Boltzmann (1844-1906) was one of the first scientists to assume that molecules in gases move at a range of speeds (previous scientists had assumed for simplicity that all molecules moved at the same speed). He calculated that gas molecules can rotate and vibrate, as well as move through space.


**UPWARDLY MOBILE**
Gases expand to fill available space. Here, the gas bromine, which is heavier than air, is confined in the lower jar. But when the separating plate is removed, the bromine molecules diffuse into the upper jar.




**BOYLE'S LAW**
Robert Boyle (p. 26) saw that when a gas is pushed into a smaller volume, it exerts greater pressure. This is because the molecules hit the container walls more frequently.



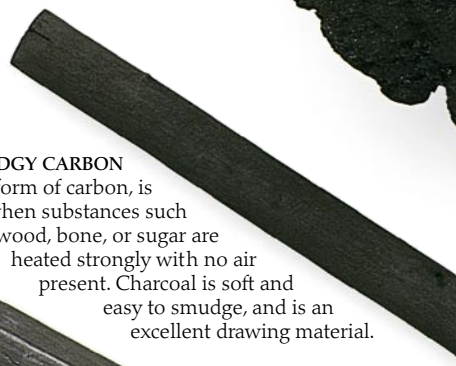

**CHARLES'S LAW**
Jacques Charles (p. 21) saw that when a gas is heated, it exerts greater pressure, and will expand if it can. The molecules move faster and collide more violently with the container walls.

# Carbon rings and chains

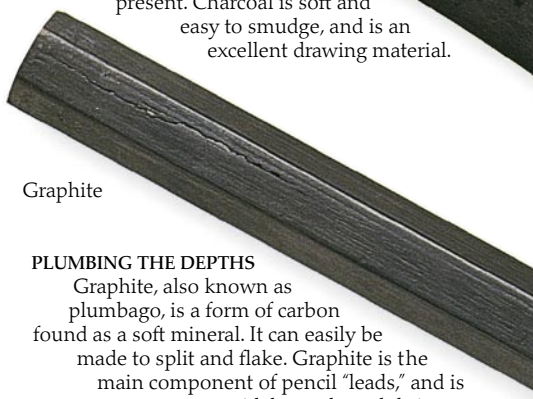
**CLOSING THE CIRCLE**
The structure of the benzene molecule, a form of carbon, resembles a snake swallowing its own tail.

CARBON IS UNIQUE in the number and complexity of compounds it can form. More than 7 million carbon-containing compounds are now known, compared with about 100,000 compounds made from all the other elements. Carbon is essential to the chemistry of all living things (pp. 42-43). The carbon atom can easily link up with other carbon atoms and with most other types of atom, using its four chemical "hooks," or valency bonds (pp. 36-37). Its molecules can have a "backbone" of a long chain of carbon atoms, either straight or branched. The carbon atoms can also form rings, which can be linked to other rings or carbon chains, to form intricate structures, sometimes consisting of thousands of atoms.

**PREHISTORIC PRESSURE**
Coal is the fossilized remains of trees and other plants that were buried in swamps. Over about 345 million years, they have been turned into a soft black rock by intense, sustained pressure from layers of other rocks. Coal consists mostly of carbon, with some hydrogen, oxygen, nitrogen, and sulfur. The carbon takes oxygen from the air and burns vigorously, so coal is a useful source of fuel.



**SMUDGY CARBON**
Charcoal, a form of carbon, is obtained when substances such as wood, bone, or sugar are heated strongly with no air present. Charcoal is soft and easy to smudge, and is an excellent drawing material.



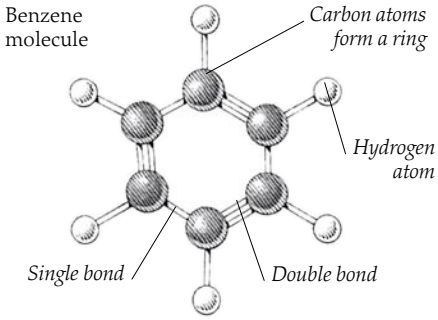
Graphite

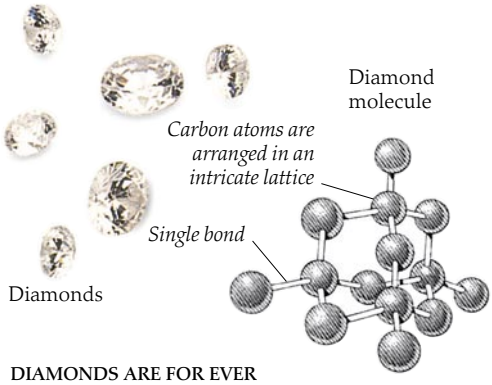
**PLUMBING THE DEPTHS**
Graphite, also known as plumbago, is a form of carbon found as a soft mineral. It can easily be made to split and flake. Graphite is the main component of pencil "leads," and is widely used as a lubricant.

Benzene

**BAFFLING BENZENE**
When coal is strongly heated, a colorless liquid – benzene – is obtained. The benzene structure is the basis of a huge number of important carbon compounds. Its molecular structure had baffled chemists until Kekulé thought of it as a ring of carbon atoms linked to hydrogen atoms.

**LORD OF THE RINGS**
Friedrich Kekulé (1829-1896) tried for a long time to calculate how a benzene molecule's six carbon atoms link to the six hydrogen atoms. He found the solution while dozing. He dreamed of a row of carbon and hydrogen atoms closing in a ring, like a snake swallowing its tail.




**DIAMONDS ARE FOR EVER**
The hardest natural material is diamond. It is a valuable gemstone, but is also used as the cutting tip in drills, or for grinding material. It consists of virtually pure carbon. Its atoms are arranged in a very strong three-dimensional lattice (a repeated pattern within a crystal). Each atom is joined to four neighbors by single chemical bonds. Diamonds form where carbon has been subjected to huge geological pressures and temperatures.

**FAT FACTS**
Butter is a mixture of fats – carbon-containing substances that are important in living things for storing energy. Similar substances that are liquid at room temperature are called oils.

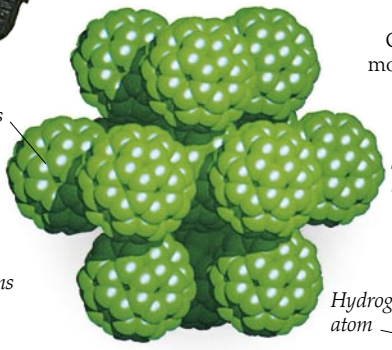

**CLEANSING WITH CARBON**
Soap is made from substances with long chains of carbon atoms, usually 15 or 17. One end of each soap molecule attaches to water and the other end attaches to oil. This enables soap to break up oil and grease into small drops in water.

Jet brooch

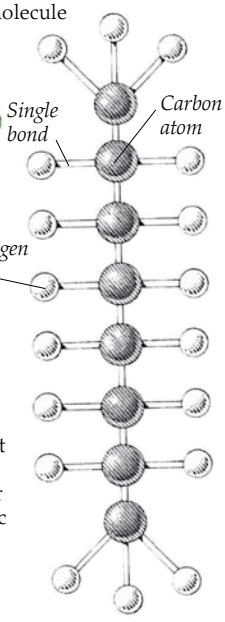


**BLACK BEAUTY**
Jet is a form of coal called lignite, and is largely made up of carbon. It has a deep velvety black color, and is easy to carve and polish. Jet has been used for jewelery since early times.

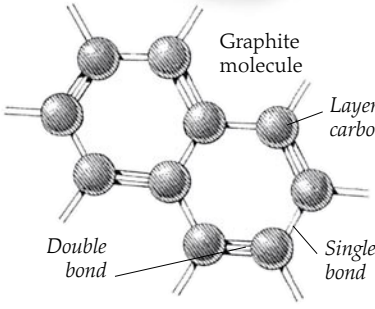
Gasoline




Octane molecule




Graphite molecule

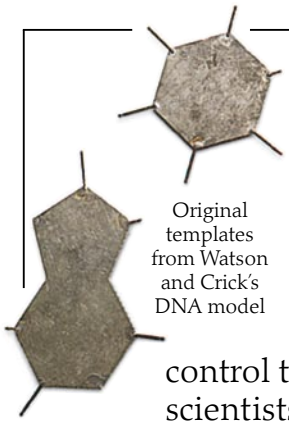



**ATOMS IN LAYERS**
Graphite and diamond are the two crystalline forms of carbon. Unlike diamond, the carbon atoms in graphite are joined in flat layers. Each layer is only weakly joined to the next, and so the layered atoms can easily slip over each other.

**GLOBULAR CARBON**
One of the strangest forms of carbon to be discovered consists of globular clusters of carbon atoms. The computer graphics color representation shown here is the simplest form, with each globe containing 60 atoms. It is named buckminsterfullerene, after Buckminster Fuller (1895-1983), an inventor who developed the similarly shaped geodesic dome. Though only recently discovered, buckminsterfullerene (also known as buckyballs) is fairly common, and can be found in soot particles.

**LIQUID POWER**
Most gasoline molecules are chains, containing between five and ten carbon atoms. The gasoline molecule octane (left) contains eight carbons. Gasoline is derived from petroleum oil, a mixture of liquids, solids, and gases that are the fossilized remains of microscopic life.

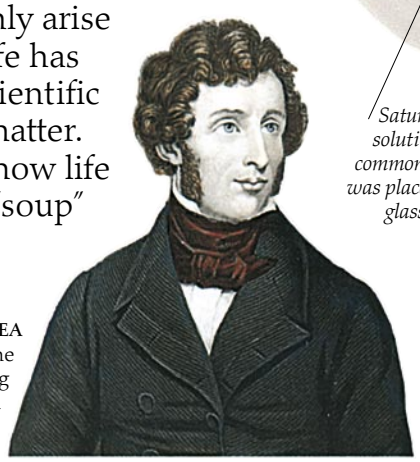
# Living matter



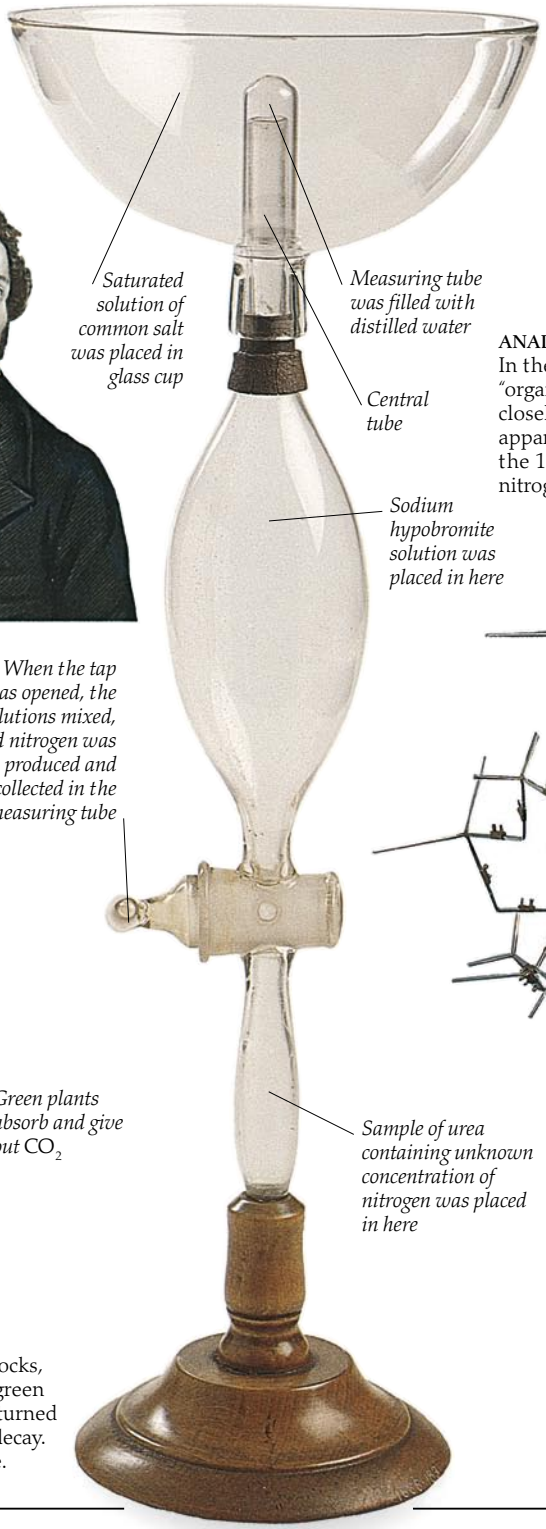
Original templates from Watson and Crick's DNA model

ANIMALS AND PLANTS ARE AMAZINGLY complex forms of living matter. They can grow, reproduce, move, and respond to their environments. Until the late 19th century, many scientists thought a "vital principle" must control the behavior of living matter. Such beliefs changed when scientists began to be able to synthesize a range of "organic" substances (substances previously found only in living things), and started to explain the chemistry of the processes within living creatures. It was once thought that flies and other small creatures could develop spontaneously from rotting matter, but Louis Pasteur (1822-1895) showed that new life can only arise from existing organisms. Life has never yet been made in a scientific laboratory from nonliving matter. This leaves the problem of how life developed on earth from a "soup" of nonliving molecules.

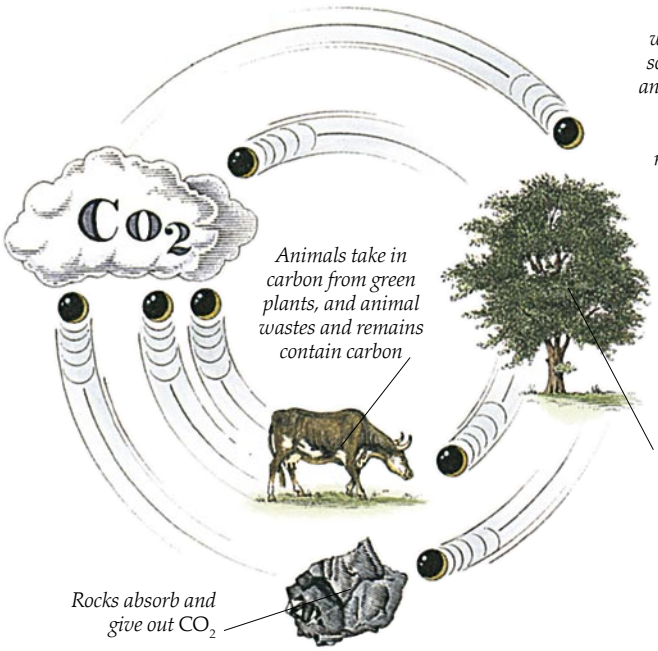
**FLIES IN THE SOUP**
In the 1860s, when Louis Pasteur boiled a flask of broth and left it, he learned that new life arises only from living matter. Dust from the air fell in the broth, and microorganisms grew. But when only dust-free air reached the broth, nothing grew.



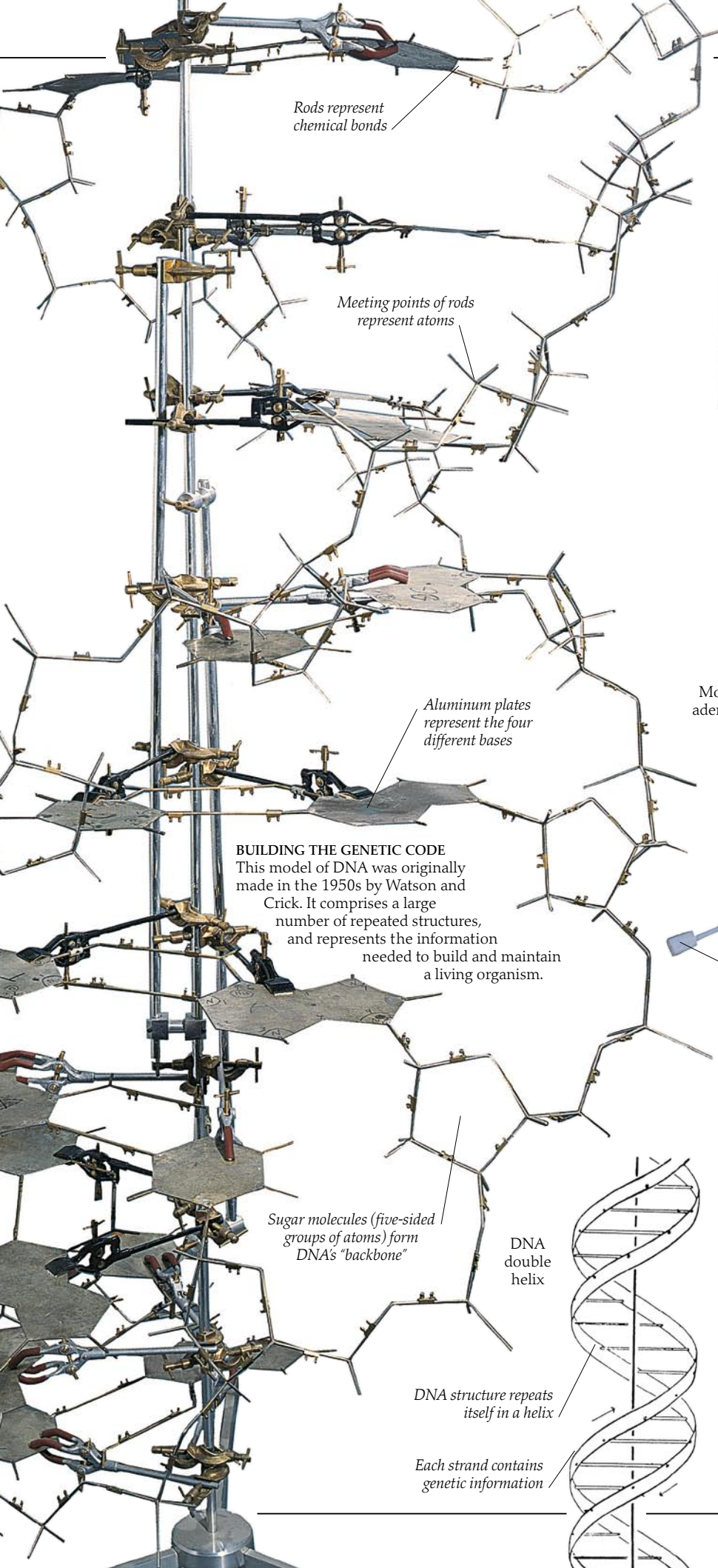
**UNDERSTANDING UREA**
A landmark in understanding life was the synthesis of urea, a nitrogen-containing chemical found in animal waste. Friedrich Wöhler (1800-1882) made urea in 1828 from ammonia and cyanic acid.



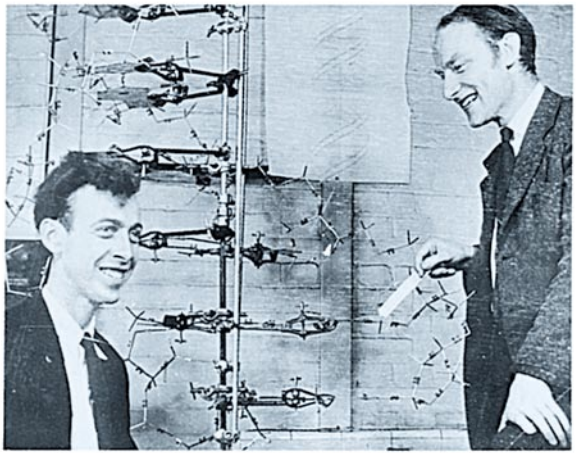

**ANALYSING THE ORGANIC**
In the 19th century many "organic" substances were closely examined. This apparatus (left) was used in the 1880s to measure the nitrogen in urea.




**NEVERENDING CYCLE**
Carbon is the basis for all living matter, circulating between air, oceans, rocks, and living things. Carbon dioxide gas ($CO_2$) is absorbed from the air by green plants. Plant-eaters use the plant's carbon for tissue-building. Carbon is returned to the environment in animals' waste products, and when dead animals decay. Rocks and water also absorb and give off $CO_2$ and complete the cycle.

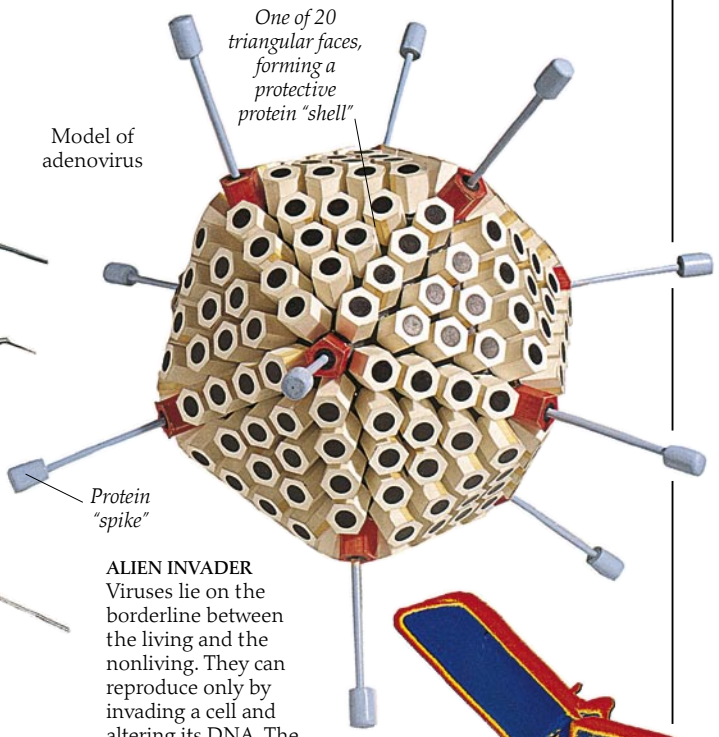



**BUILDING THE GENETIC CODE**
This model of DNA was originally made in the 1950s by Watson and Crick. It comprises a large number of repeated structures, and represents the information needed to build and maintain a living organism.

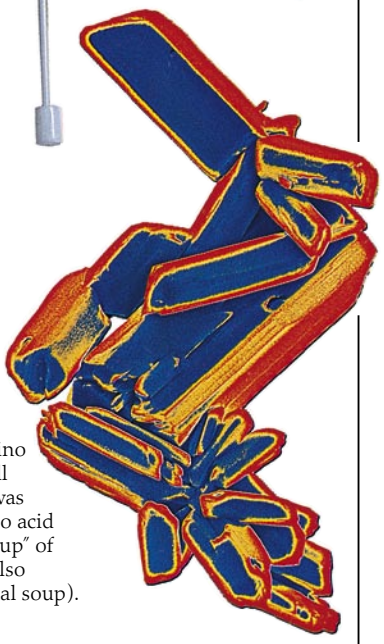


**SOLVING THE PUZZLE**
In 1953 American James Watson (1928-) and Englishman Francis Crick (1916-) discovered a vital clue to the secret of living matter – the structure of DNA (deoxyribonucleic acid). This substance, found in living cells, passes genetic "information" from parents to offspring. DNA has two chains of atoms linked in a double helix (like a spiral staircase). The "stairs" are groups of atoms called bases. The sequence of bases spells out the genetic "message."

Model of adenovirus




**ALIEN INVADER**
Viruses lie on the borderline between the living and the nonliving. They can reproduce only by invading a cell and altering its DNA. The cell then becomes a factory for making more viruses.



**EARLIEST ACID**
These are highly magnified crystals of glycine, an amino acid. There are about 20 amino acids found in nearly all living things. Glycine was probably the first amino acid to be formed in the "soup" of nonliving molecules (also known as the primordial soup).

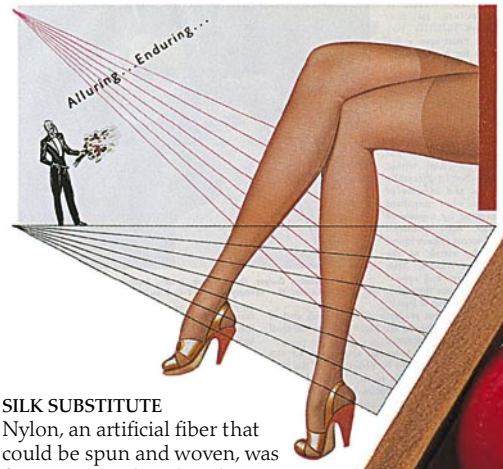
# Designing molecules


Artificial teeth and dental plate from the 1870s

**In the mid-19th century** chemists began to use their new knowledge of organic molecules (pp. 42-43) to make new materials with valuable properties. Parkesine, an imitation ivory, was made in 1862 by Alexander Parkes (1813-1890). In 1884 Hilaire de Chardonnet (1839-1924) made rayon, the first artificial fiber, by imitating the chemical structure of silk. Rubber was toughened and made more useful by the vulcanizing process (heat treatment with sulfur), invented in 1839. The age of plastics was ushered in by Leo Baekeland (1863-1944), who invented Bakelite in 1909. Plastics are polymers – large molecules with possibly thousands of identical groups of atoms chained together. Plastics can be molded by heat and pressure, but then become fixed in shape. They are unreactive, and do not disturb the body's chemistry when used as a replacement hipjoint, for example. Plastics pose a waste disposal problem, however, for most are not biodegradable. In addition to plastics, modern chemists have designed many useful products, such as drugs, detergents, and alloys.


**BAEKELAND'S BAKELITE**
The first entirely synthetic plastic, bakelite was used in early telephones and other electrical devices. It was developed in the United States in 1909.

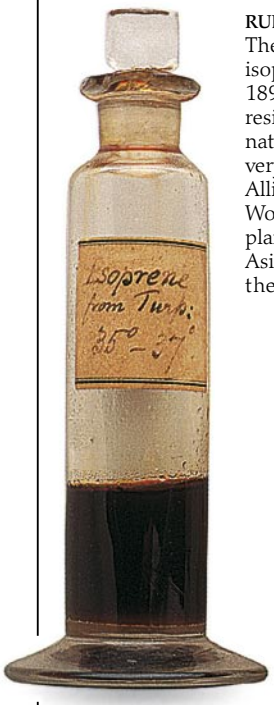

**EBONITE ARTIFACT**
This saxophone mouthpiece is made of ebonite, a type of vulcanized rubber. It is also known as vulcanite.




**SILK SUBSTITUTE**
Nylon, an artificial fiber that could be spun and woven, was first mass-produced in the 1940s. It was mainly used in stockings and underwear.



Bakelite hairdryer




**RUBBER WEAR**
The synthetic rubber isoprene was made in 1892. It is much more resistant to wear than natural rubber. It became very important to the Allies during the Second World War, when rubber plantations in Southeast Asia were captured by the Japanese.


Samples of isoprene

**FLEXIBLE HARDNESS**
These billiard balls are made of celluloid, a hard plastic. It is also flexible, and was used as a base for photographic film, and in shirt collars.

**A BALATA BALL**
Balata, a hard, rubberlike substance, is used for the outer casing of golf balls. Natural balata is now extremely rare, and has had to be replaced by synthetic plastics.


**IN THE FRAME**
A tough high-density form of polyethylene is used for spectacle frames. Polyethylene is most familiar as packaging.

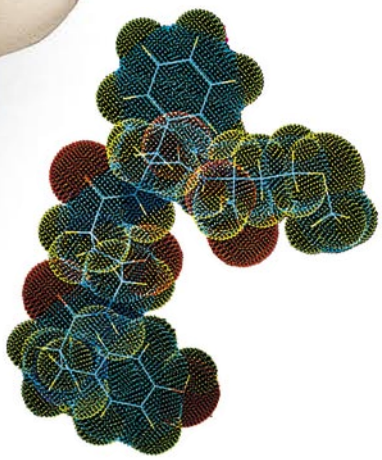
**MARBLED FOUNTAIN**
Plastic cases made fountainpens cheaper. Their "marbled" appearance was created by mixing different colored plastics.

**PLASTIC PLATTER**
This plastic plate is a thermoset – it has been hardened by heating during its manufacture, and is consequently heat-resistant.



**HOT STUFF**
Bakelite is a good thermal and electrical insulator, and was used in items such as this 1930s hairdryer.

**PLASTIC PERSONALITY**
The plastic Michelin Man advertises Michelin car tires, which are made of vulcanized rubber.



**SCREEN TEST**
Chemists now work with molecules on computer screens. This is a molecule of enkephalin, a natural substance in the brain that affects the perception of pain. The atoms in the molecule are color-coded, positioned, and in their correct proportions. Their positions can be modified, or new groups can be added. The computer has stored information about the forces between the atoms (pp. 60-61), so chemically impossible groupings are not permitted. The proposed molecule can be rigorously tested on screen, and precious laboratory research time can be saved.

# Radioactivity

**BECQUEREL'S RAYS**
While studying Xrays (radiation that could penetrate certain materials) Antoine Becquerel (1852-1908) stumbled on a new kind of invisible, penetrating radiation. In 1896 he found that crystals of a uranium compound could "fog" photographic film, even when the film was wrapped in black paper.

In 1880 the atom was still thought to be impenetrable and unchanging. However, by 1900 this picture was seen to be incorrect. An important new discovery was radioactivity. This is the emission of invisible radiations by certain kinds of atoms, happening spontaneously and unaffected by chemical reactions, temperature, or physical factors. The radiations are alpha, beta, or gamma ($\alpha$, $\beta$, or $\gamma$). Ernest Rutherford (1871-1937) did most to clarify radioactivity. He found that $\alpha$-particles were helium atoms, without electrons (pp. 48-49) and $\beta$-particles were fast electrons. When $\alpha$- or $\beta$-particles were shot out from the atom, a different sort of atom was left. Such changes could cause $\gamma$-radiation, a type of electromagnetic radiation, to be emitted. Transmutation, long dreamed of by the alchemists as they tried to change one element into another, really was possible. It is now known that radiations in large doses, or in small exposures over long periods, can cause sickness and death. Nevertheless, radioactivity has many important uses. For example, metal objects can be "X-rayed" with $\gamma$-rays, medicines moving around the body can be tagged with radioactive "tracers," and archaeological finds can be dated by measuring their radioactivity.

Cartoon of the Curies

**A CURIOUS COUPLE**
Marie Curie (1867-1934), assisted by her husband Pierre (1859-1906), found that the uranium ore pitchblende was considerably more radioactive than pure uranium. They realized that pitchblende must contain additional, more highly radioactive substances. In 1902, after four years of laborious effort, they isolated tiny quantities of two new elements, polonium and radium. Like other early scientists working with radioactivity, the Curies knew little of its dangers, and Marie Curie died of leukemia. The high radiation levels with which she worked are evident from her glass flask – exposure to radiation turned it from clear to blue.

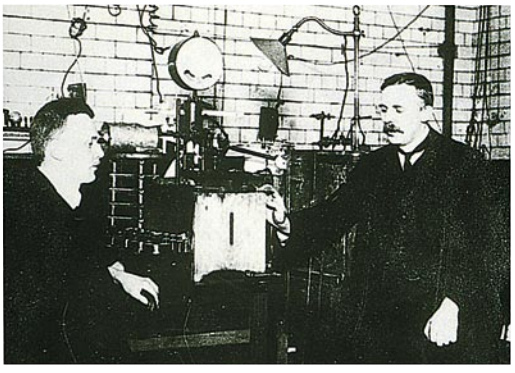
Marie Curie's glass flask

**URANIUM ORE**
Pitchblende is a brownish-black rock consisting mainly of uranium chemically combined with oxygen. It forms crystals called uraninite. Once considered useless, pitchblende is now the main source of uranium and radium.

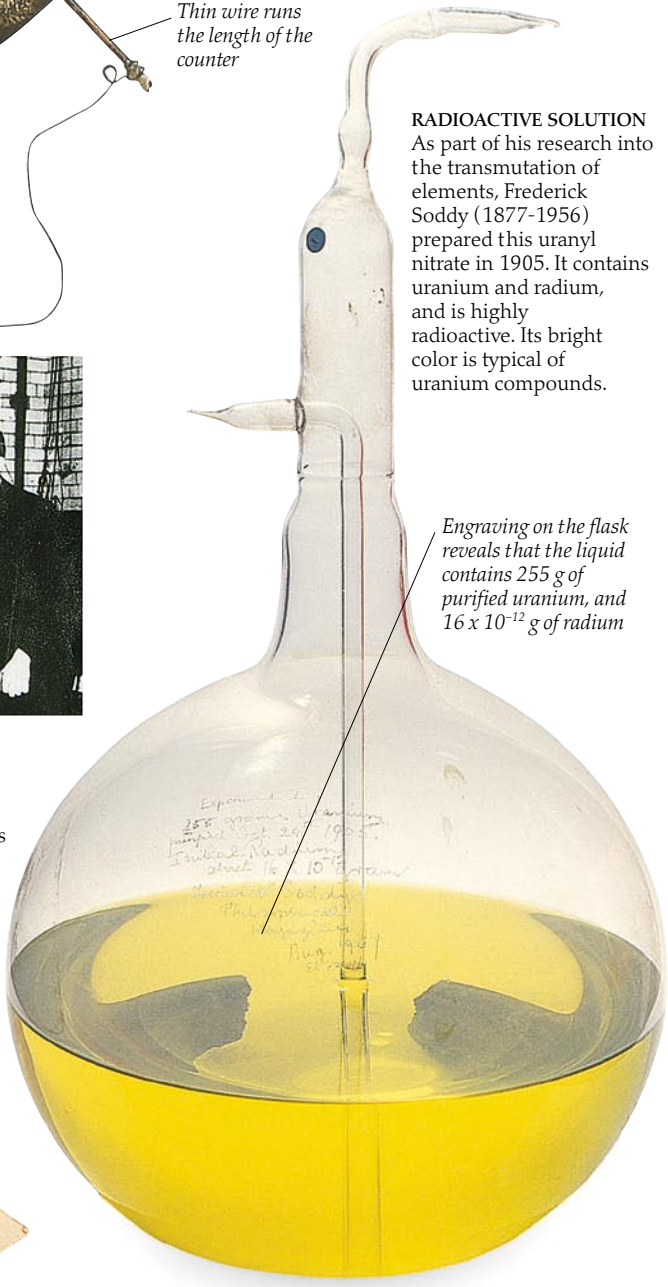
**FLASH GADGET**
William Crookes (p. 48) invented the spinthariscope for detecting $\alpha$-particles. The $\alpha$-particles struck a screen coated with zinc sulfide, creating a tiny flash seen through the eyepiece.


**GEIGER'S GAUGE**
Hans Geiger (1882-1945) gave this Geiger counter, a device for measuring radiation levels, to James Chadwick (pp. 52-53) in 1932. In this early model, low-pressure gas is contained in a copper cylinder, fitted with a handle. An electrical voltage is applied between this casing and a thin wire running along its center. When an α- or β-particle enters the counter through a window at one end, it generates a brief burst of electric current between the case and the wire, which is detected on the counter.

**RADIATION OF THE ROCKS**
A low level of "background" radioactivity is present in everything, even in our bodies. Levels are higher in regions of granite rock, for granite contains uranium. Granite emits radon gas, which can accumulate in homes and threaten health.

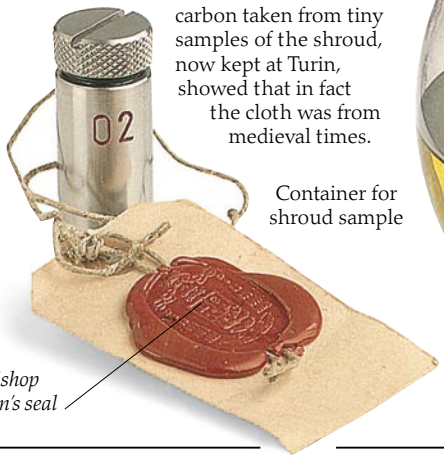


**PHYSICISTS AT WORK**
Ernest Rutherford (right) and Hans Geiger in their laboratory at Manchester University in England, about 1908, with apparatus for detecting α-particles. Geiger and Rutherford realized that α-particles were helium atoms without electrons.




**RADIOACTIVE SOLUTION**
As part of his research into the transmutation of elements, Frederick Soddy (1877-1956) prepared this uranyl nitrate in 1905. It contains uranium and radium, and is highly radioactive. Its bright color is typical of uranium compounds.

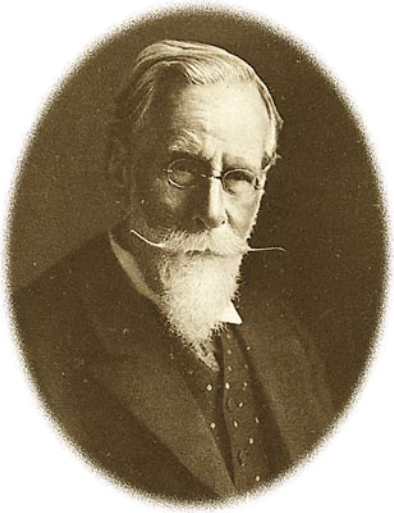
Part of image on shroud




**CARBON DATING THE TURIN SHROUD**
The body of the crucified Christ was reputedly wrapped in a shroud, and was said to have created a life-size image still visible on the cloth. Analysis of a radioactive form of carbon taken from tiny samples of the shroud, now kept at Turin, showed that in fact the cloth was from medieval times.

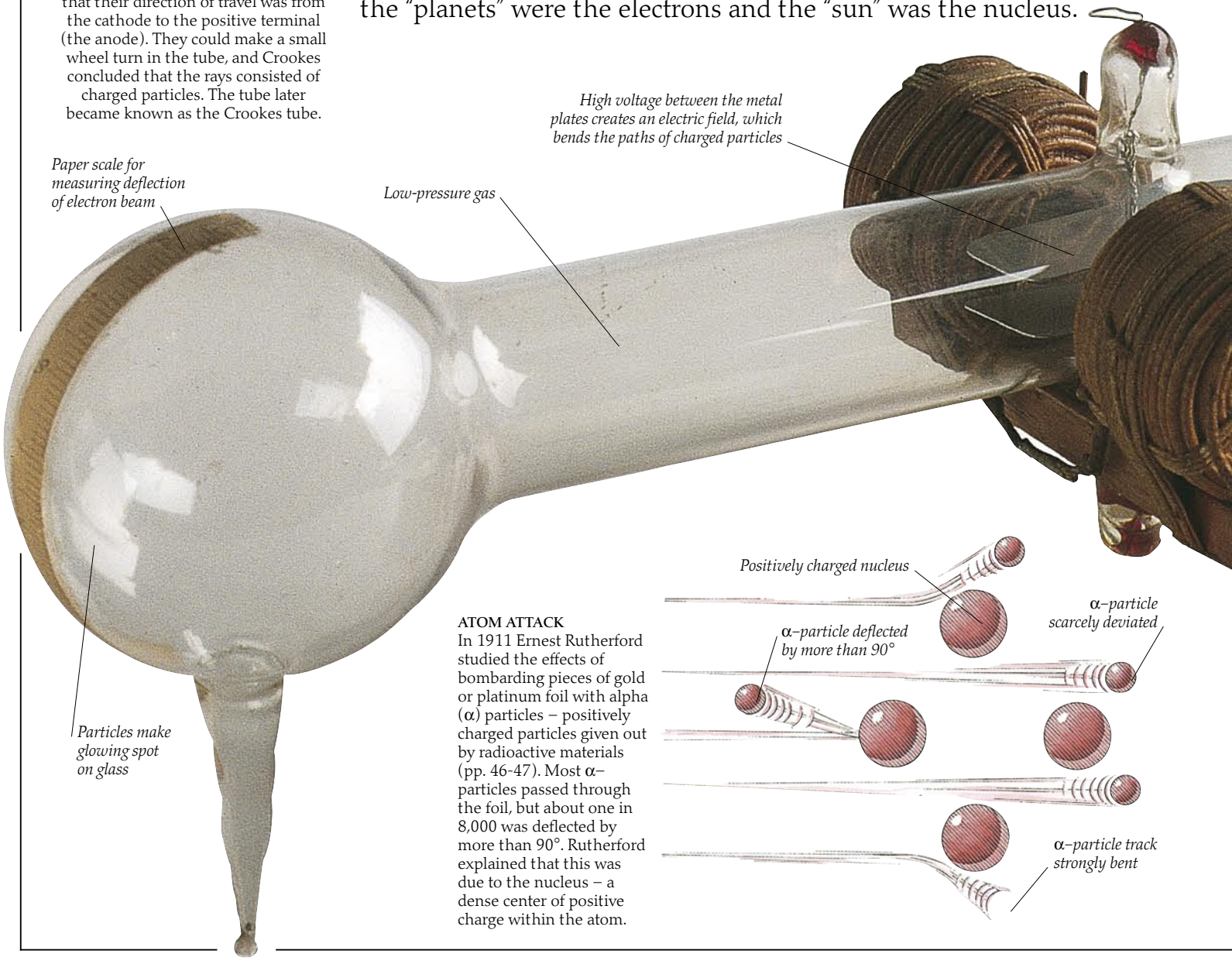
Container for shroud sample

# Inside the atom

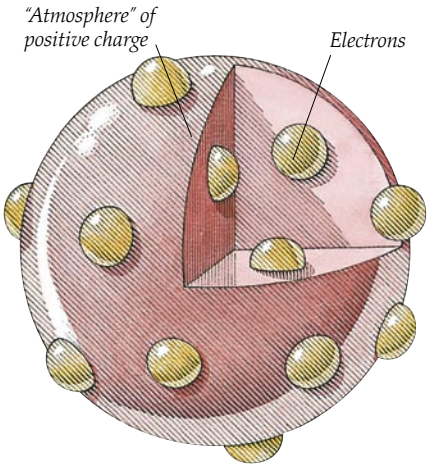


**MYSTERY RAYS**
William Crookes (1832-1919) devised a glass tube that could contain a vacuum. It was used for the study of cathode rays (electrons emitted by a cathode – a negative terminal – when heated). He placed small obstacles in the rays, which cast "shadows," showing that their direction of travel was from the cathode to the positive terminal (the anode). They could make a small wheel turn in the tube, and Crookes concluded that the rays consisted of charged particles. The tube later became known as the Crookes tube.

**THE FIRST CLUE TO THE STRUCTURE** of the atom came from experiments by English physicist J. J. Thomson (1856-1940) in 1897. He discovered particles that were smaller than atoms in cathode rays. These rays were seen passing between high voltage terminals in a glass tube filled with low pressure gas. The particles, called corpuscles by Thomson and later known as electrons, had a negative electric charge and were about 2,000 times lighter than a hydrogen atom. They were exactly the same whatever gas was used in the tube, and whatever metal the terminals were made of. This strongly suggested that electrons were present in all matter. Atoms must also contain positive electric charge to balance the negative charge of electrons. Ernest Rutherford (pp. 46-47) probed atoms with particles produced in his radioactivity experiments, and found that the positive charge was concentrated in a tiny nucleus. He reached the conclusion that the atom resembled a miniature solar system, where the "planets" were the electrons and the "sun" was the nucleus.

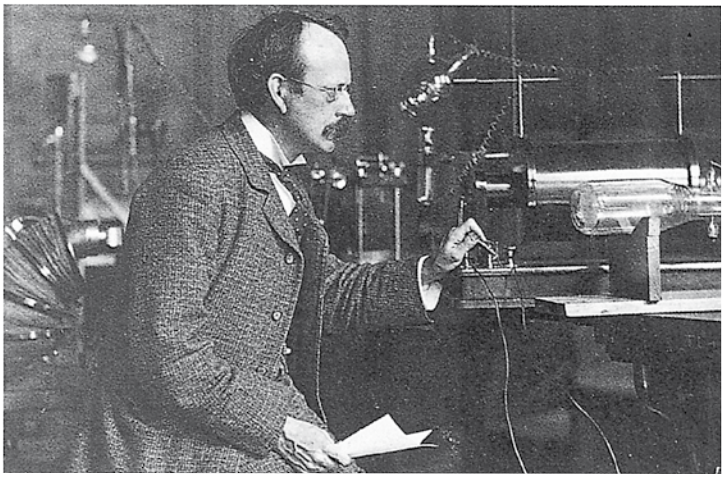


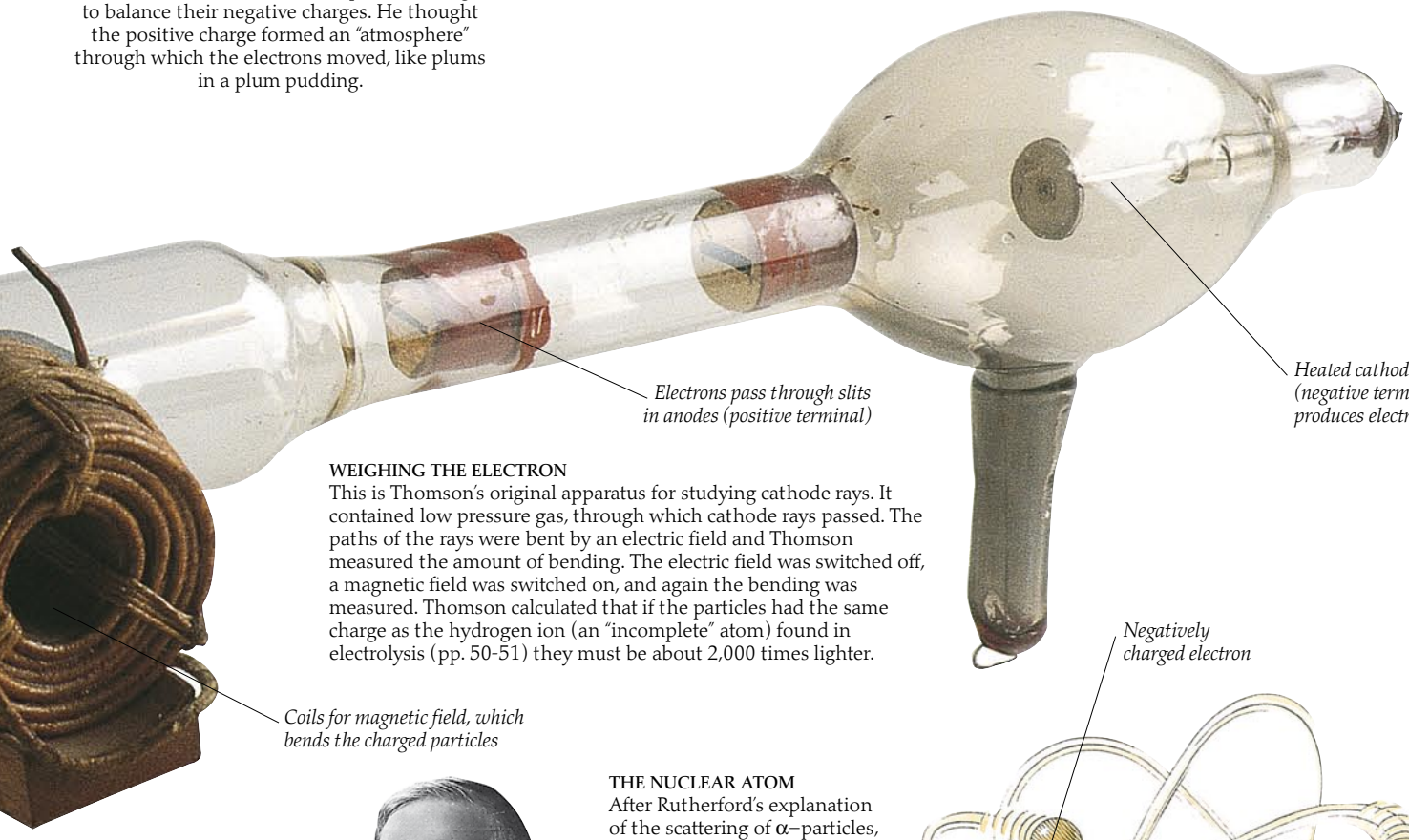

**ATOM ATTACK**
In 1911 Ernest Rutherford studied the effects of bombarding pieces of gold or platinum foil with alpha (α) particles – positively charged particles given out by radioactive materials (pp. 46-47). Most α–particles passed through the foil, but about one in 8,000 was deflected by more than 90°. Rutherford explained that this was due to the nucleus – a dense center of positive charge within the atom.



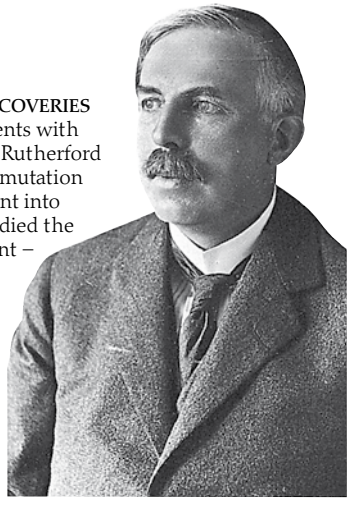

**THE PLUM PUDDING ATOM**
In his plum pudding theory, J. J. Thomson suggested that every atom consists of a number of electrons, and an amount of positive charge to balance their negative charges. He thought the positive charge formed an "atmosphere" through which the electrons moved, like plums in a plum pudding.

**THOMSON'S DISCOVERIES**
J. J. Thomson intended to be an engineer, but instead became a brilliant physicist. He studied cathode rays with great success because he managed to achieve very low gas pressures in his modified Crookes tube. Thomson's discovery of the electron — the fundamental unit of electric current, present in all matter – revolutionized the theories of electricity and atoms. He also confirmed the existence of isotopes (pp. 52-53) – elements that each have several types of atoms, chemically identical, but differing in weight.



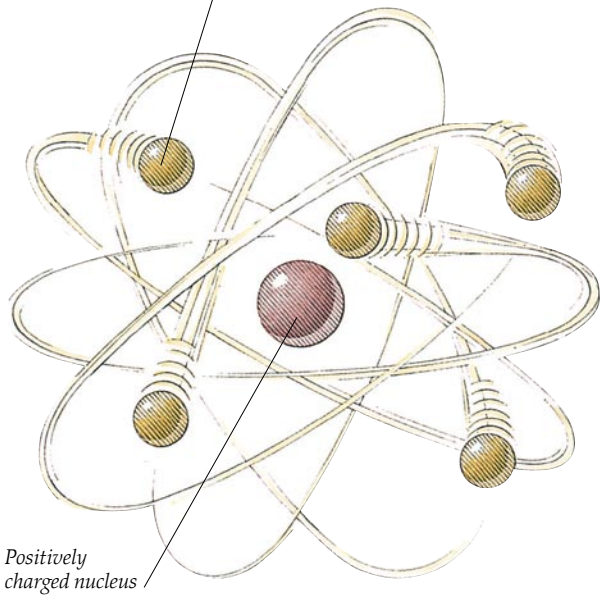



**WEIGHING THE ELECTRON**
This is Thomson's original apparatus for studying cathode rays. It contained low pressure gas, through which cathode rays passed. The paths of the rays were bent by an electric field and Thomson measured the amount of bending. The electric field was switched off, a magnetic field was switched on, and again the bending was measured. Thomson calculated that if the particles had the same charge as the hydrogen ion (an "incomplete" atom) found in electrolysis (pp. 50-51) they must be about 2,000 times lighter.



**RUTHERFORD'S DISCOVERIES**
During his experiments with radioactivity, Ernest Rutherford discovered the transmutation (p. 46) of one element into another. He also studied the half-life of an element – the time taken for half of a sample of a radioactive element to decay, or change into another element. He published his discoveries in 1904 in his book *Radioactivity*.

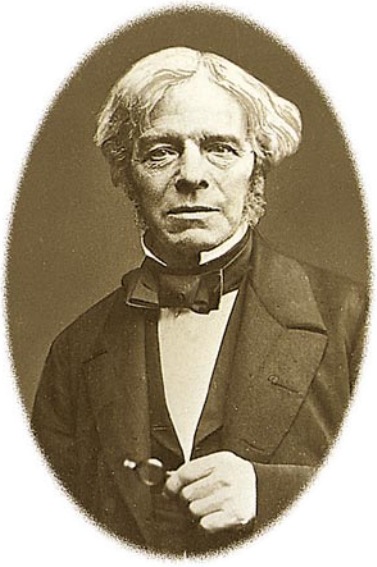
**THE NUCLEAR ATOM**
After Rutherford's explanation of the scattering of α–particles, the structure of the atom became clearer. Negatively charged electrons were thought to move around a positively charged, dense nucleus, much like planets moving around the sun. However, there were problems with this "solar-system" model. According to the laws of physics at that time, such an atom should have collapsed instantly in a burst of electromagnetic radiation. (It is now known that the atom does not collapse because electrons are only "allowed" certain energies, pp. 50-51.)



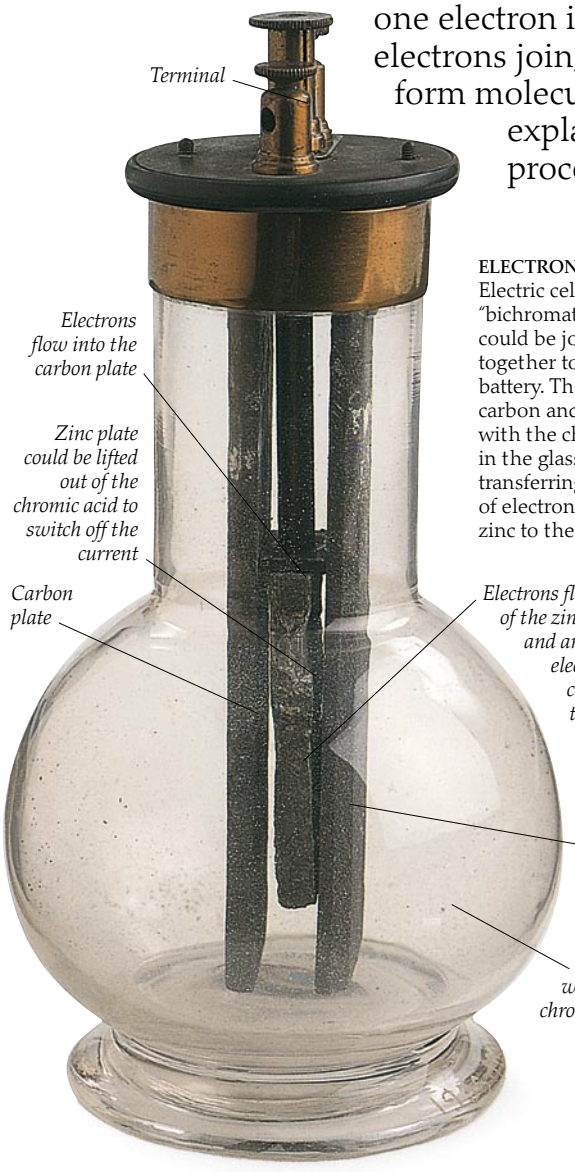
# Electrons, shells, and bonds

**THE EXPENSE OF EROS**
In 1884 this aluminum statue of the Greek god Eros was highly expensive, but now aluminum can be cheaply produced by electrolysis.

In the early 1900s the structure of the atom became clearer, but the laws of physics at the time could not explain why electrons did not quickly spiral in toward the nucleus. Niels Bohr (1885-1962), a student of Rutherford, helped to solve the mystery by suggesting that electrons were only "allowed" certain energies. He found that electrons with the lowest allowed energy orbit closest to the nucleus, and electrons with the highest allowed energy orbit furthest away. It was soon discovered that there is a limit to the number of electrons with each energy. Electrons in an atom behave as if they are stacked, lowest energies first, in "shells" around the nucleus. It is the electrons in an atom's outermost shell that decide an atom's chemical properties. Atoms with outer shells "filled" with electrons are less reactive than those with only one electron in their outer shell. The outermost electrons join, or bond, with other atoms to form molecules. This new picture of the atom explained the reactions of atoms in processes such as electrolysis.

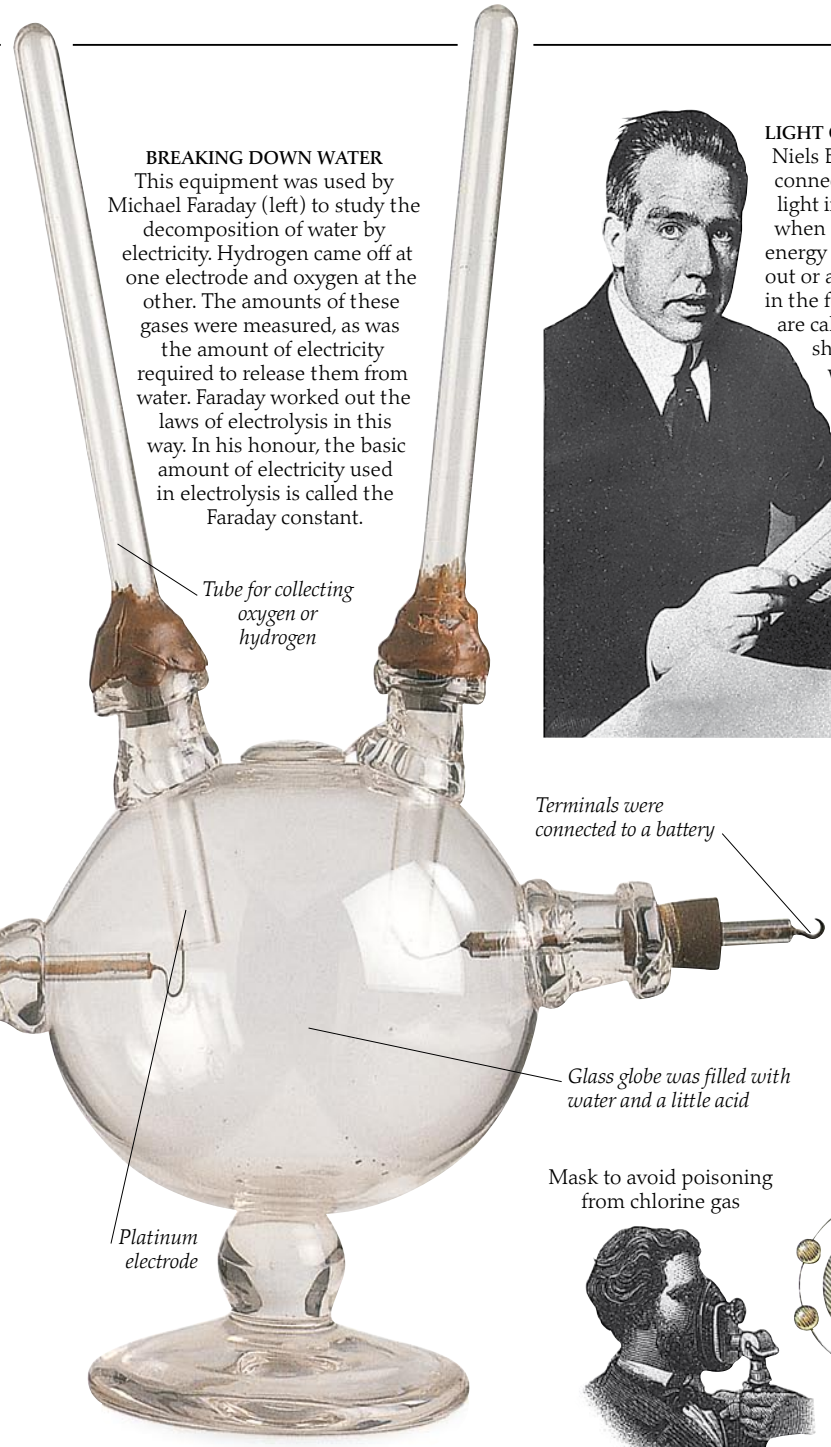


**LIBERATING LAWS**
Michael Faraday (1791-1867) discovered the laws of electrolysis in 1832. He found that elements are liberated by a certain amount of electricity, or by twice or three times this amount. This depends on the number of outer electrons.

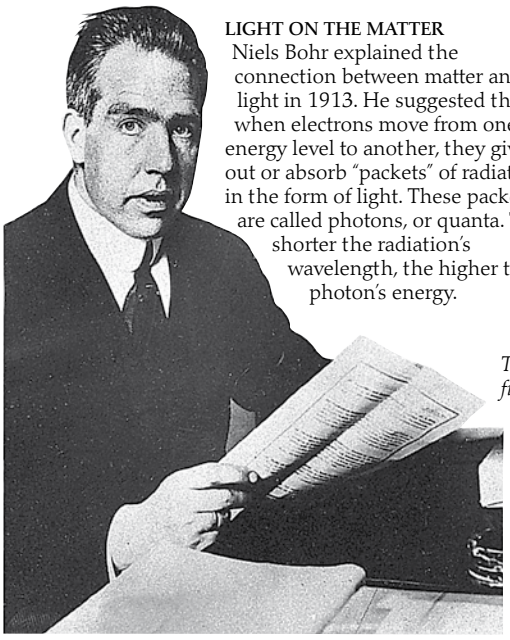



**ELECTRON STREAMS**
Electric cells like this "bichromate cell" could be joined together to make a battery. The plates of carbon and zinc react with the chromic acid in the glass jar, transferring a stream of electrons from the zinc to the carbon.

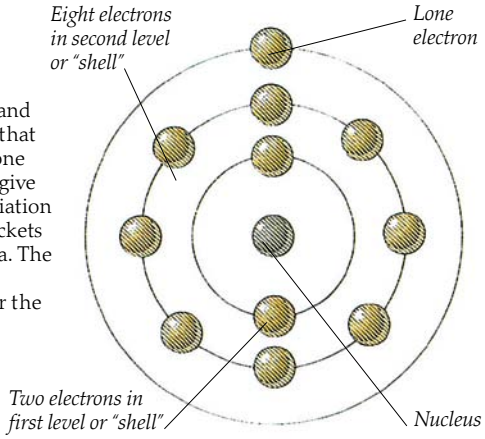
**ELECTRIFYING DISCOVERIES**
In the 19th century many new elements were discovered by passing electric current through solutions or molten materials. The samples of metals shown here were prepared by electrolysis, and the electric current came from a battery. Electrolysis can separate compounds into elements by supplying electrons to, or removing them from, the outer shells of atoms.




**BREAKING DOWN WATER**
This equipment was used by Michael Faraday (left) to study the decomposition of water by electricity. Hydrogen came off at one electrode and oxygen at the other. The amounts of these gases were measured, as was the amount of electricity required to release them from water. Faraday worked out the laws of electrolysis in this way. In his honour, the basic amount of electricity used in electrolysis is called the Faraday constant.

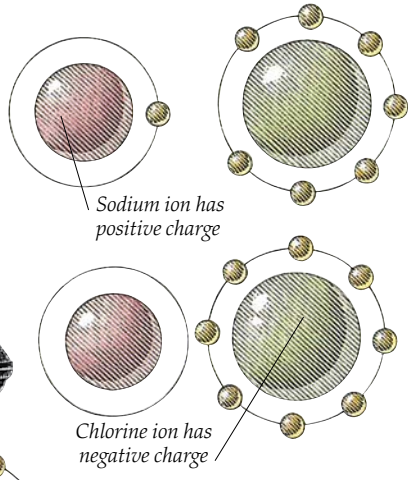


**LIGHT ON THE MATTER**
Niels Bohr explained the connection between matter and light in 1913. He suggested that when electrons move from one energy level to another, they give out or absorb "packets" of radiation in the form of light. These packets are called photons, or quanta. The shorter the radiation's wavelength, the higher the photon's energy.



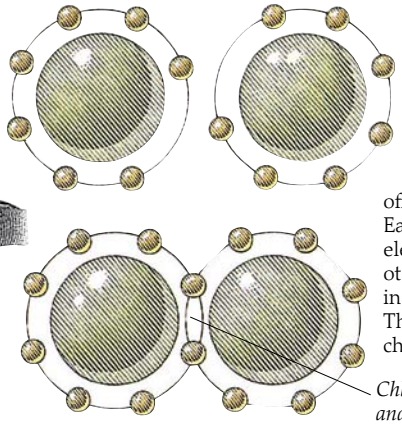

**BOHR'S ATOM**
In Bohr's theory of the atom, electrons that are farther out from the nucleus have higher energy, and an electron can jump to a higher level by absorbing energy. This can happen at high temperatures, or when photons with enough energy hit the atom. If there is a gap in a lower level, an electron can fall down to that level, giving out energy in the form of radiation.

**IONIC BONDS**
Sodium and chlorine ions are held together by their opposing electric charges. The sodium atom "wants" to lose its outer electron because the atom is unstable, and the incomplete atom (ion) is left with a positive electric charge. A chlorine atom "wants" to gain an electron to fill its outer shell, and gains an extra negative charge.

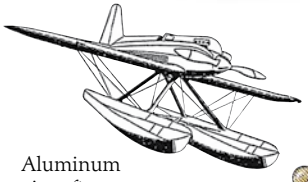



Sodium chloride – common salt

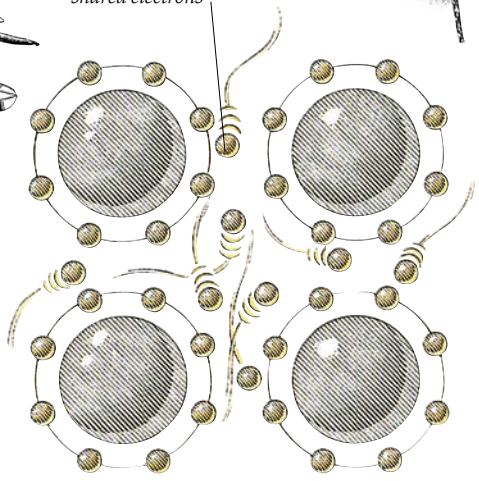
Mask to avoid poisoning from chlorine gas




**COVALENT BONDS**
Atoms can share electrons in their outer shells to produce filled shells, forming a "covalent" bond. Chlorine atoms, with seven electrons in the outer shell, can pair off, each pair sharing two electrons. Each atom effectively has eight electrons in the outer shell. Like many other gases, chlorine normally exists in the form of two-atom molecules. The bond is easily broken, making chlorine reactive and dangerous.

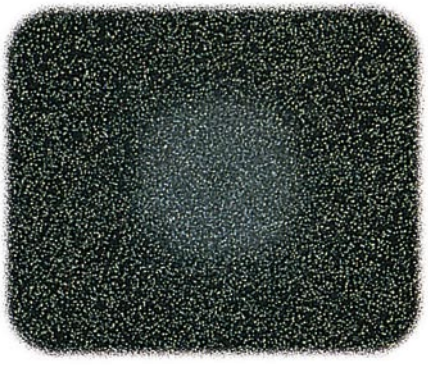


Aluminum aircraft



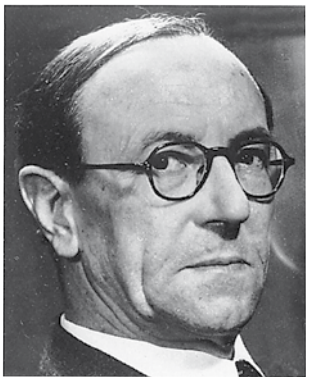

**METALLIC BONDS**
The atoms of metals share their outer electrons. They are contributed to a "pool," and wander freely from atom to atom. The electrons' ease of movement is why metals are good conductors of heat and electricity.

**CLOUDS OF MYSTERY**
Bohr's sharply defined electron orbits have been superseded by fuzzy electron "clouds" (right), which can be seen with an electron microscope. It is now known that electrons behave as waves, as well as like particles. An electron is most likely to be found where the electron "cloud" is dense. But there is always a definite, if small, chance of finding it closer to, or farther from, the nucleus.

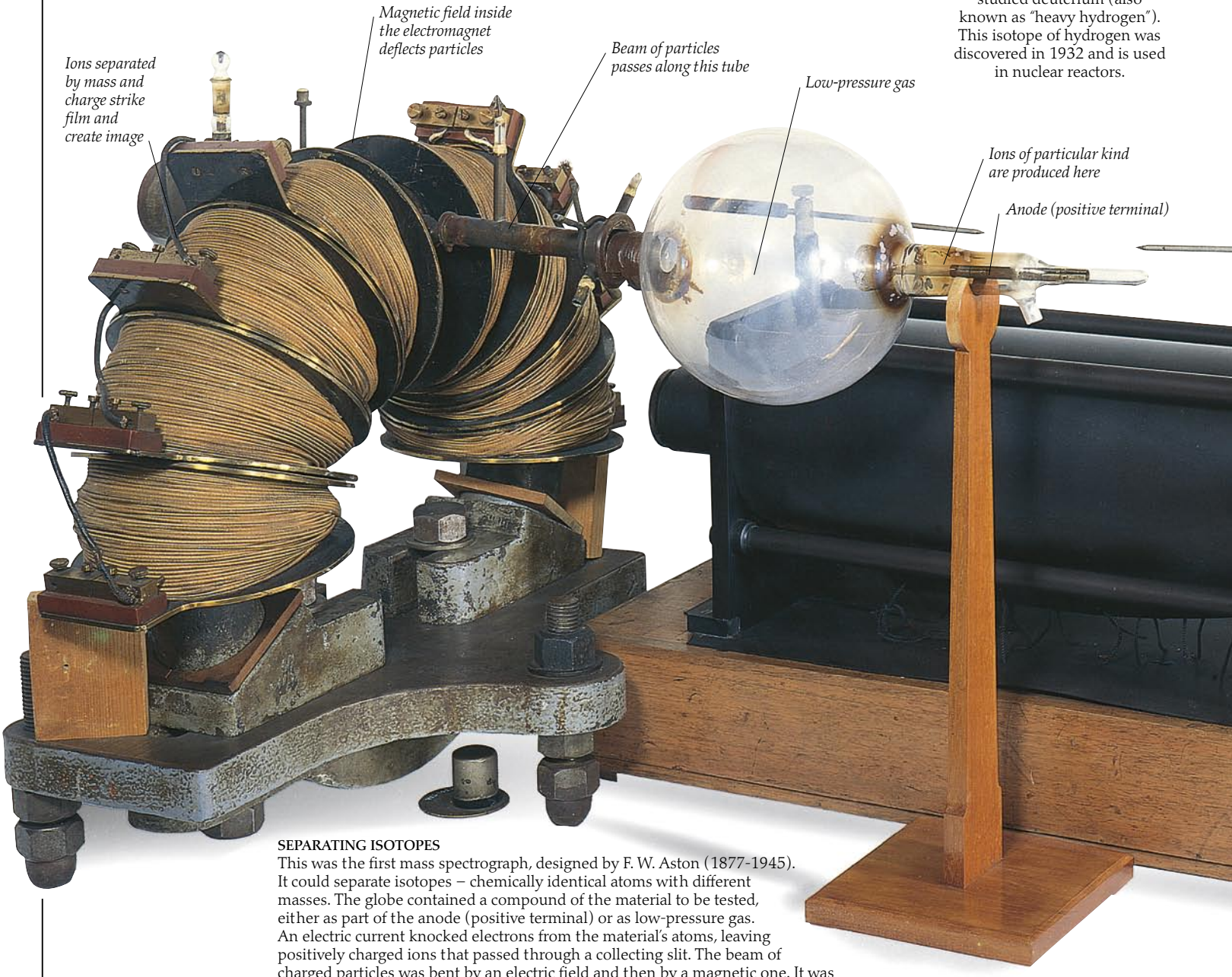


# Architecture of the nucleus

By the early 20th century, it was known that the atom had a positively charged nucleus. Ernest Rutherford (pp. 46-47) suggested that the nucleus contained positively charged particles called "protons" (Greek for "first things"). He demonstrated their existence in 1919 by knocking them out of nitrogen nuclei using alpha (α) particles. James Chadwick (1891-1974) discovered another particle in the nucleus in 1932 – the neutron, an uncharged particle of about the same mass as the proton. All nuclei comprise protons and neutrons. The number of protons determines the number of electrons circling the nucleus, and therefore the chemical properties of the atom (pp. 50-51). All elements have different isotopes – atoms with the same number of protons but different numbers of neutrons.



**PARTICLE DISCOVERER**
James Chadwick, a student of Rutherford, discovered neutrons by exposing the metal beryllium to α-particles. He observed a new kind of particle ejected from its nucleus, the neutron. Later he studied deuterium (also known as "heavy hydrogen"). This isotope of hydrogen was discovered in 1932 and is used in nuclear reactors.

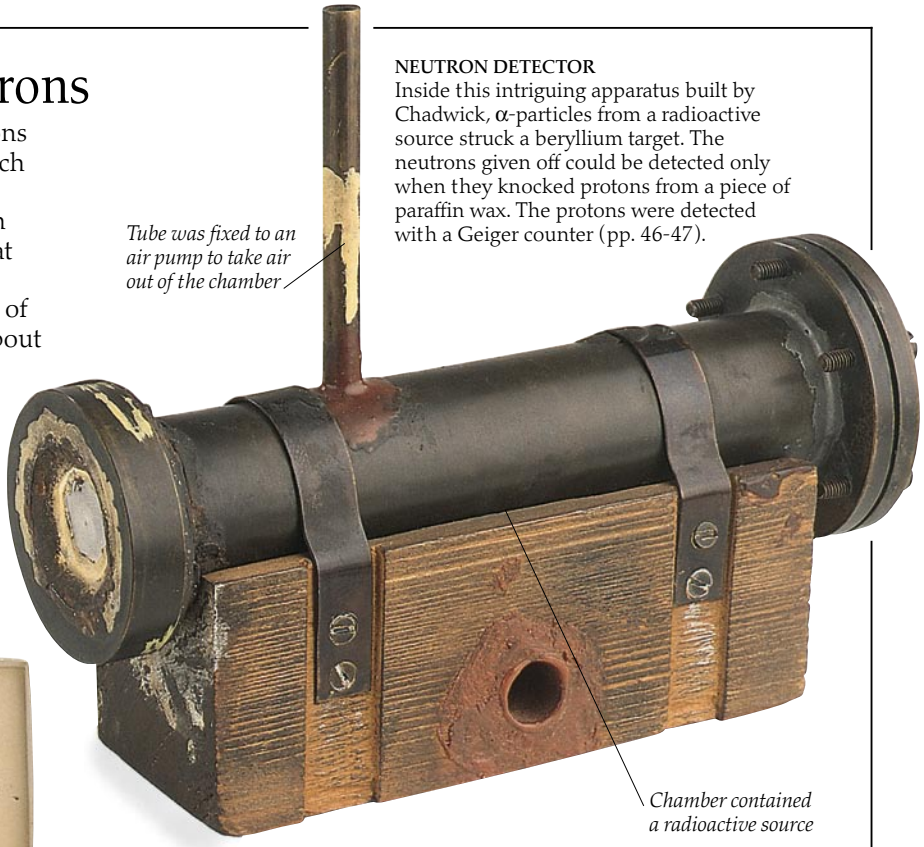



**SEPARATING ISOTOPES**
This was the first mass spectrograph, designed by F. W. Aston (1877-1945). It could separate isotopes – chemically identical atoms with different masses. The globe contained a compound of the material to be tested, either as part of the anode (positive terminal) or as low-pressure gas. An electric current knocked electrons from the material's atoms, leaving positively charged ions that passed through a collecting slit. The beam of charged particles was bent by an electric field and then by a magnetic one. It was spread into separate bands on a photographic film, according to the ions' charge and mass.

# Electrons, protons, and neutrons

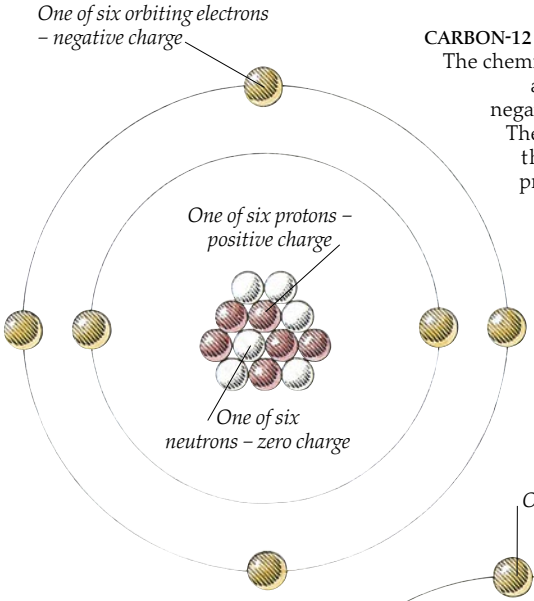
Rutherford believed the nucleus was made up of protons and a smaller number of electrons. He thought that each electron was closely paired with a proton to make a "doublet" that was neutral (had zero electric charge). In 1932 James Chadwick produced a type of radiation that did not bend in an electric field, but was far more penetrating than gamma rays. This radiation consisted of uncharged particles, known as "neutrons," that were about as massive as hydrogen atoms. Chadwick realized that these neutrons might be particles themselves, and not a proton and electron combined. This view is now accepted. However, a free neutron has a 50 percent chance of "decaying" into a proton and electron in 15 minutes. If a proton and electron collide they will produce a neutron.

**NEUTRON DETECTOR**
Inside this intriguing apparatus built by Chadwick, α-particles from a radioactive source struck a beryllium target. The neutrons given off could be detected only when they knocked protons from a piece of paraffin wax. The protons were detected with a Geiger counter (pp. 46-47).

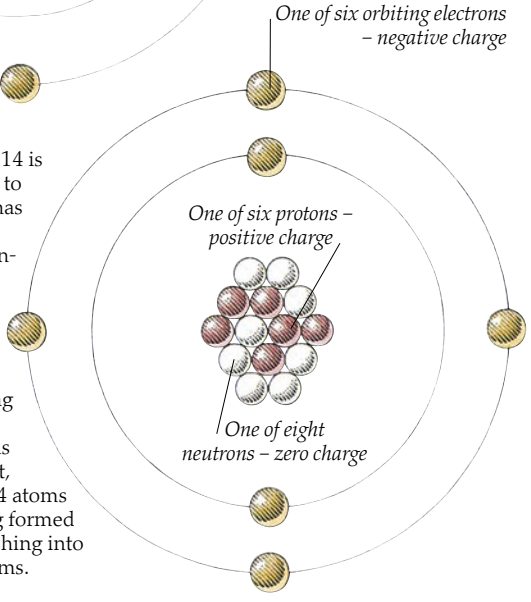



**A SCIENTIST'S TOOLS**
This cigarette carton was Chadwick's "toolbox." He used the pieces of paraffin wax to observe neutrons. The silver and aluminum foils, of different thicknesses, were used as barriers to determine the penetrating power of the radiation.



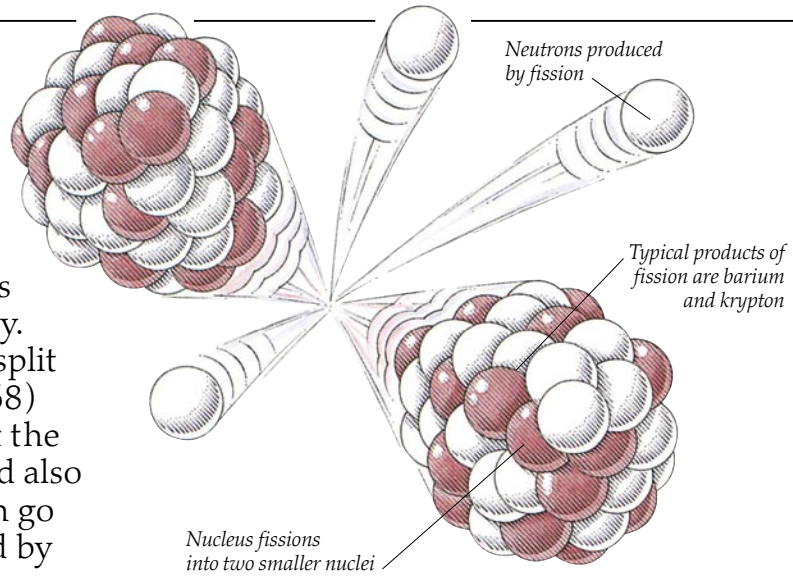



**CARBON-12**
The chemical properties of carbon are determined by its six negatively charged electrons. These six electrons balance the six positively charged protons of the nucleus. In a carbon-12 atom, the nucleus also has six neutrons, of about the same mass as the protons, giving the atom a "mass number" of 12.



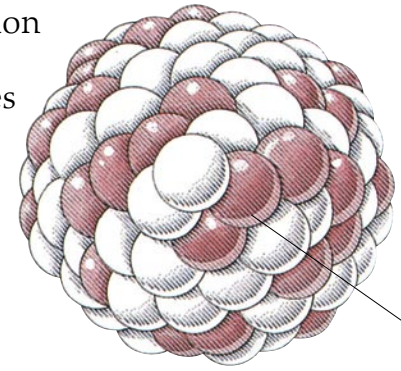

**CARBON-14**
The isotope carbon-14 is chemically identical to ordinary carbon. It has six protons and six electrons. But carbon-14 has two extra neutrons, giving it a mass number of 14. This isotope is radioactive, 50 percent of it decaying every 5,730 years. Environmental levels are roughly constant, since new carbon-14 atoms are constantly being formed by cosmic rays smashing into ordinary carbon atoms.

# Splitting the atom




**After the discovery** of the nucleus in 1911, it was found that bombarding certain atoms with particles from radioactive materials could disintegrate their nuclei, releasing energy. The heaviest nuclei, those of uranium, can be split by neutrons in this way. Otto Hahn (1879-1968) and Lise Meitner (1878-1968) discovered that the uranium nucleus splits in half, or "fissions," and also gives out further neutrons. These neutrons can go on to cause further fissions. In 1942 a team led by Enrico Fermi (1901-1954) achieved this "chain reaction" in the world's first nuclear reactor. Three years later the chain reaction was used in the nuclear bombs that destroyed the Japanese cities of Hiroshima and Nagasaki.

**CHAIN REACTION**
The source of energy in a nuclear reactor or a nuclear explosion is a chain reaction. A nucleus of uranium or plutonium splits (fissions), giving out neutrons that split further nuclei. Immense heat is created by the energy of the splitting fragments and by radiation. In a reactor this heat is used in a controlled way to generate electricity. In an explosion it is released violently.

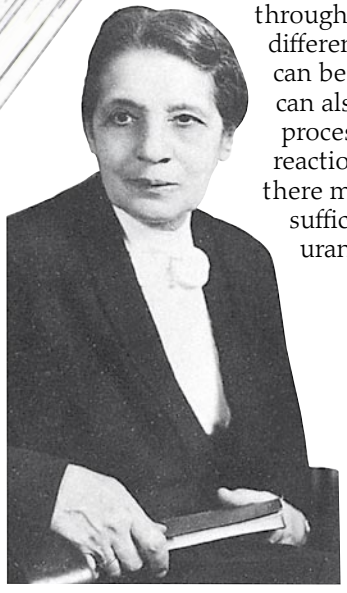



**2 NUCLEAR SPLIT**
When a neutron hits another uranium nucleus, the nucleus fissions into two smaller nuclei of approximately half the size. Several neutrons are also given out, together with high-energy radiation. The neutrons can go on to cause further fissions in a chain reaction. Neutrons can be slowed down by graphite or heavy water mixed with the uranium.

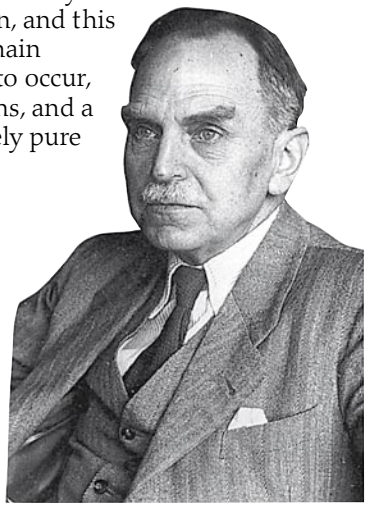

**1 WANDERING NEUTRONS**
Neutrons can be released by bombarding atoms with radiation. Neutrons are also occasionally given out by decaying uranium nuclei, but these neutrons rarely react with uranium nuclei to build a chain reaction. Many nuclear reactors use uranium-235, a very reactive but uncommon isotope.

## Unstable uranium

The main isotope of uranium is uranium-238 (symbol U-238). It has 238 particles in its nucleus – 92 protons and 146 neutrons. The neutrons prevent the protons from blowing the nucleus apart because of their mutual repulsion. Even so, an unstable U-238 nucleus breaks down from time to time, giving out an alpha ($\alpha$) particle and turning into a thorium nucleus. The thorium nucleus in turn breaks down, and so do its products, in a chain of decays that ends when a lead nucleus is formed. Other uranium isotopes go through a similar chain of radioactive decays, ending in a different isotope of lead. This is why uranium-bearing rocks can be detected by their radioactivity. Uranium can also break down by fission, and this process can build up into a chain reaction. For a chain reaction to occur, there must be special conditions, and a sufficient quantity of relatively pure uranium must be used.



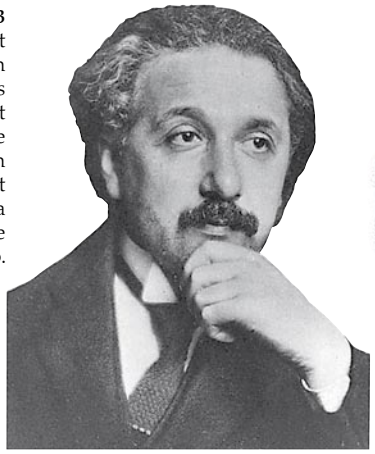
**FAMILY FISSION**
In 1917 Lise Meitner and Otto Hahn discovered a new element, protactinium, found in uranium ores. In 1939 Meitner and her nephew Otto Frisch (1904-1979) announced the fission of uranium.

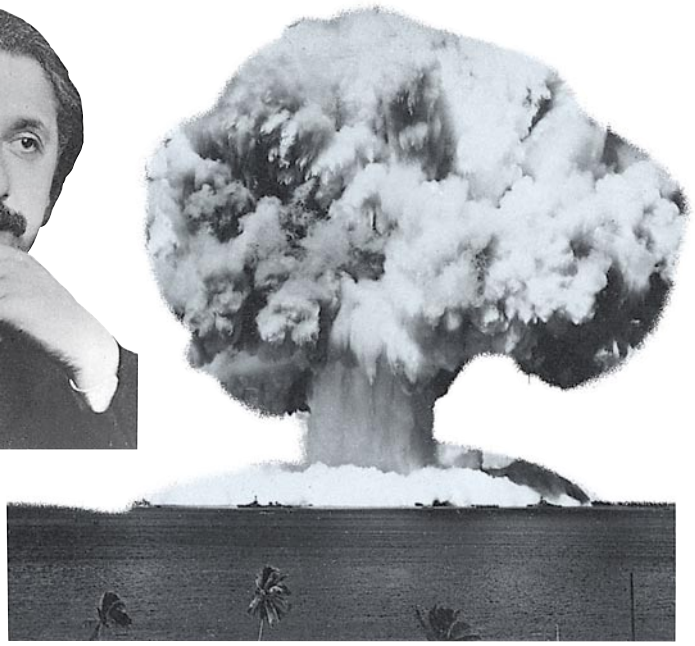


**PUZZLING PRODUCT**
Otto Hahn studied the disintegration of uranium nuclei by neutrons. Among the by-products of this disintegration were barium nuclei, which are about half the weight of uranium nuclei.


**HEAVY WATER**
Neutrons in a nuclear reactor's chain reaction can be controlled by a moderator such as heavy water. It is 11 percent heavier than an equal volume of ordinary water.

**PROPHET OF THE BOMB**
In 1905, 40 years before the first nuclear explosion, Albert Einstein (1879-1955) showed in his Theory of Special Relativity that energy and mass can be converted into each other. In 1939 he warned President Franklin Roosevelt that a uranium chain reaction could be used in a powerful new bomb.





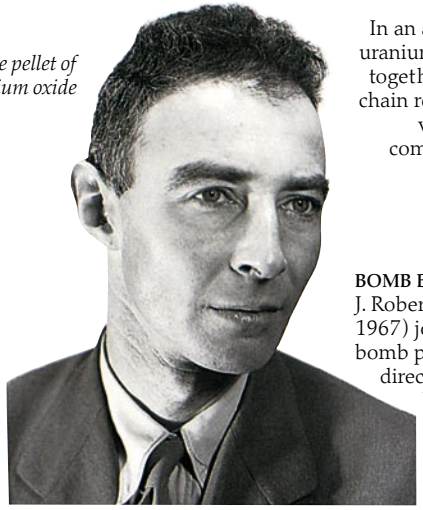
**BLOW-UP**
In an atomic explosion pieces of uranium or plutonium are hurled together by explosives to form a chain reaction. In the explosion a very tiny amount of matter completely disappears (p. 28).


**RODS IN THE REACTOR**
These fuel rods are used in Magnox nuclear reactors. The rods consist of long bars of natural uranium, clad in magnox, a magnesium alloy. In the reactor carbon dioxide gas flows around the rods, carrying away the generated heat.

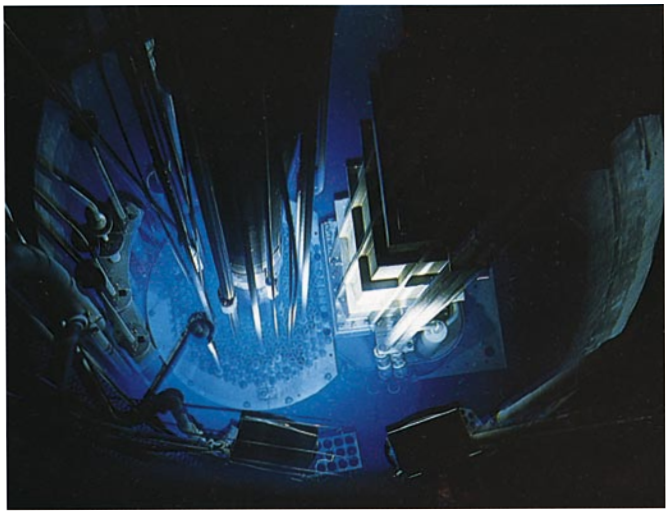
*Fuel rods are about 5 ft (about 5 m) long*

*Single pellet of uranium oxide*

**A RICHER FUEL**
This fuel rod contains pellets of a compound of uranium, uranium dioxide, containing a high proportion of uranium-235. These rods are used in the Magnox reactor and the British Advanced Gas-cooled Reactor (AGR).

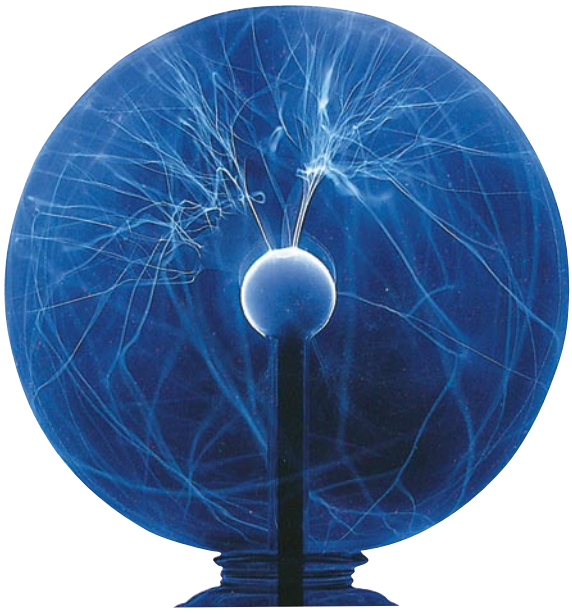


**BOMB BUILDER**
J. Robert Oppenheimer (1904-1967) joined the US atomic bomb project in 1942, and was director of the laboratory that built the first nuclear bombs. His atomic research ended when his security clearance was withdrawn in 1954.



**LIGHT AT THE CORE**
The eerie blue glow in the heart of this nuclear reactor is called Cherenkov radiation. It is caused by electrons from radioactive fuel plowing through water and giving out light. The chain reaction in a nuclear reactor can be controlled by rods containing a neutron-absorbing material such as cadmium. The intense heat of the reactor's core is carried away by gas, liquid metal, or high-pressure water.

# Hot matter

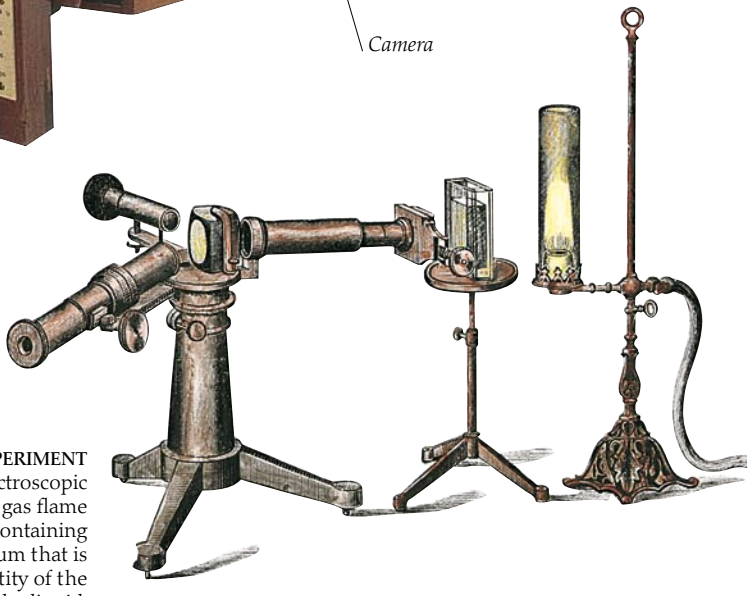


**INSIDE THE PLASMA BALL**
A powerful voltage at the center of this glass globe tears electrons from the atoms of the low-pressure gases inside. Avalanches of electrons build up, forming bright squiggly lines of hot gas. The mixture of electrons and charged atoms in these lines is called a plasma.

ATOMS ARE LAID BARE as they are subjected to high temperatures. The spectroscope reveals their secrets by analyzing the light they give out. In a spectroscope the light falls on a diffraction grating – a flat surface with thousands of lines – or a prism. Light passes through or is reflected, and is broken up into different colors. Sunlight consists of the whole color spectrum and beyond. Gases at the sun's surface produce sunlight, at temperatures of about 10,000° F (about 5,500° C). Here, the atoms' outer electrons are knocked to higher orbits and give out light as they fall back (pp. 50-51). Inside the sun and other high-temperature stars, inner electrons are knocked to higher orbits. As they fall back, they give out ultraviolet and X-rays. At the centers of the sun and stars, at temperatures of about 27 million° F (around 15 million° C), nuclei are stripped bare and welded together, producing heavier nuclei.

**A LIGHT SIGNATURE**
The spectrometer "reads the signature" of materials by analyzing their light. The light first passes through a narrow slit into a small telescope, which focuses the light into a narrow parallel beam. The beam passes through a glass prism, and is spread out, with each wavelength (color) of light going in a slightly different direction. Through a viewing telescope a rainbow-colored "spectrum" can be seen. This may appear as a host of bright lines, or a continuous band of color, crossed by dark lines, where wavelengths have been absorbed.


**THE VANISHING SUN**
The sun is kept at a high temperature by the flood of energy from the nuclear reactions at its heart. Every second, four million tons of the sun's matter vanish, converted into energy that escapes from the surface as radiation.

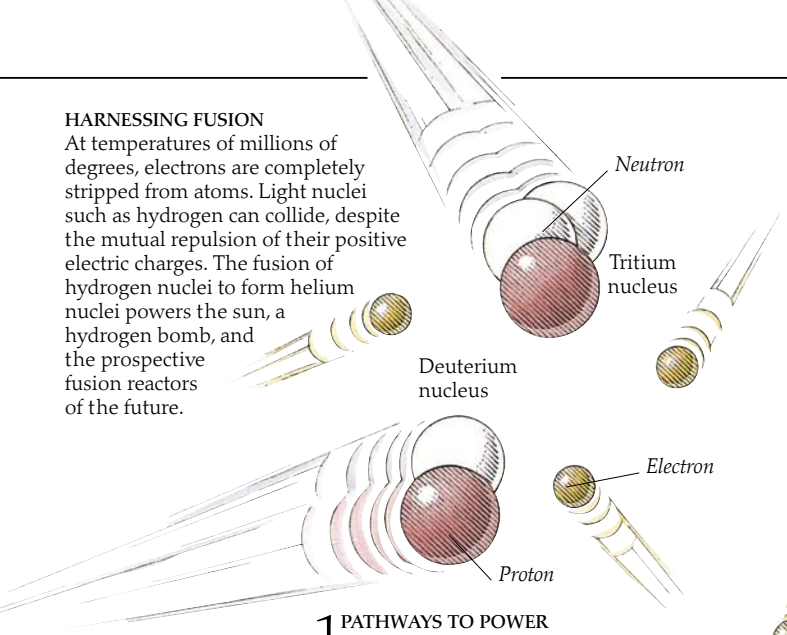


**ABSORBING EXPERIMENT**
This 19th-century spectroscopic experiment shows light from a gas flame passing through a liquid containing dissolved materials. The spectrum that is produced reveals the identity of the dissolved materials in the liquid.

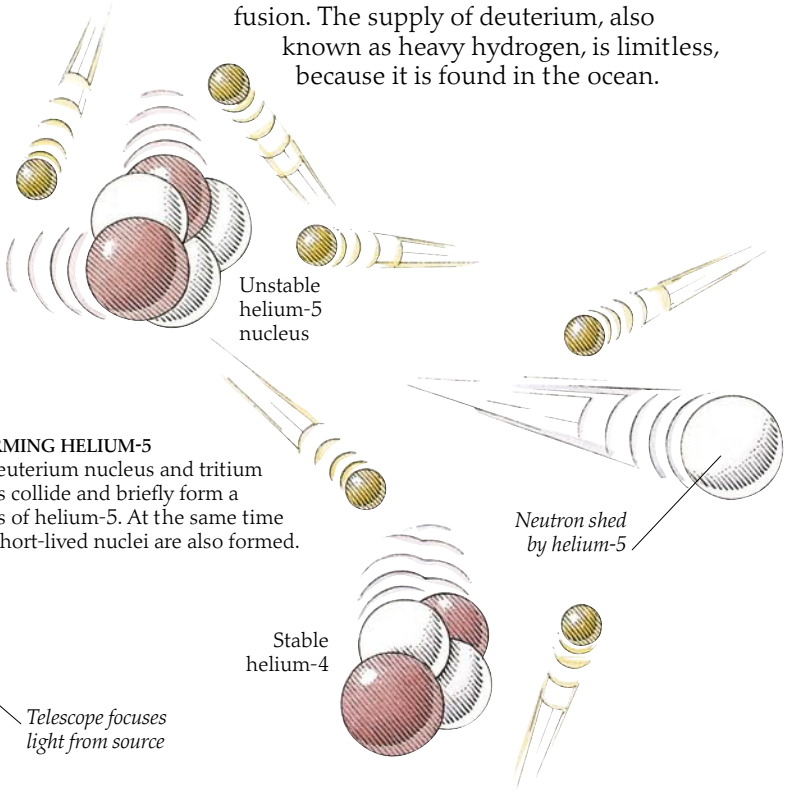
# Building nuclei by fusion

Merging (fusing) light nuclei yields an immense amount of energy. Hydrogen has the very lightest nucleus, containing just one proton. Hydrogen nuclei can be fused to form one nucleus of helium (two of the protons are turned into neutrons, forming a helium nucleus with two protons and two neutrons). Energy is given out at the same time. This fusion process takes place in the sun and stars in a series of stages, with other nuclei forming briefly, then changing into other nuclei. On earth, hydrogen isotopes such as deuterium and tritium are used for fusion. The supply of deuterium, also known as heavy hydrogen, is limitless, because it is found in the ocean.

**HARNESSING FUSION**
At temperatures of millions of degrees, electrons are completely stripped from atoms. Light nuclei such as hydrogen can collide, despite the mutual repulsion of their positive electric charges. The fusion of hydrogen nuclei to form helium nuclei powers the sun, a hydrogen bomb, and the prospective fusion reactors of the future.

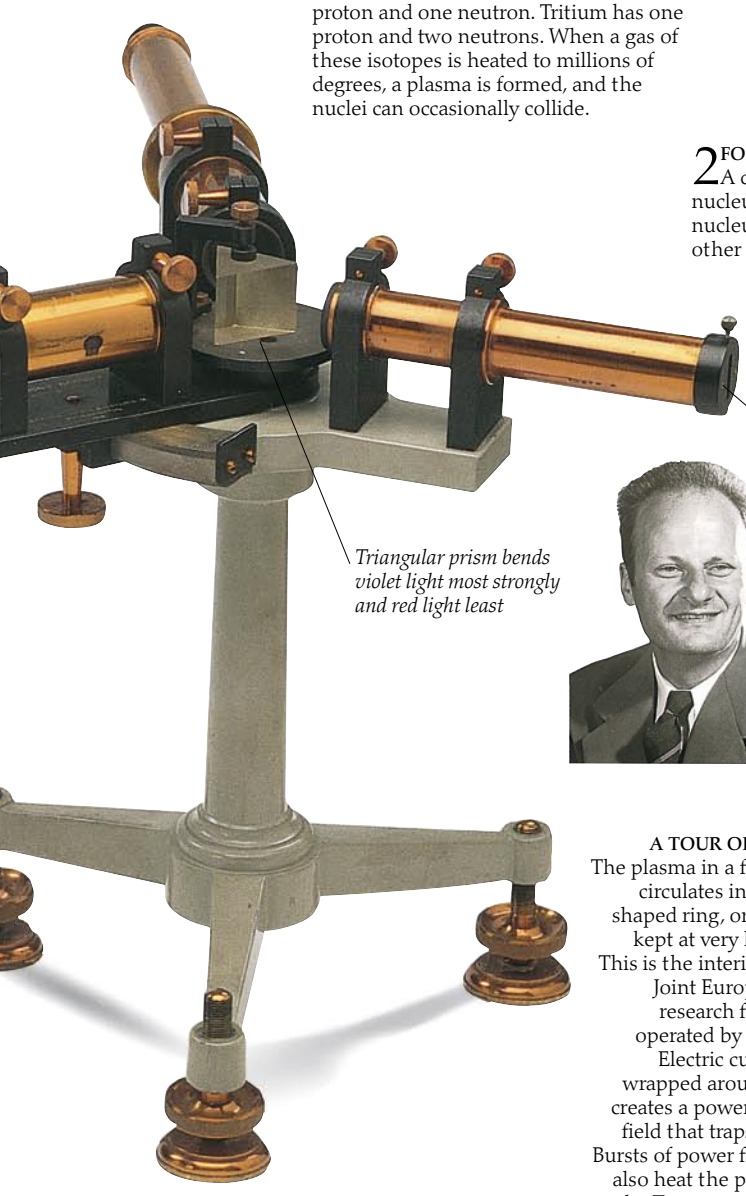



**1 PATHWAYS TO POWER**
There are several ways in which helium nuclei can form from hydrogen nuclei. One process involves two isotopes of hydrogen – deuterium and tritium. The deuterium nucleus has one proton and one neutron. Tritium has one proton and two neutrons. When a gas of these isotopes is heated to millions of degrees, a plasma is formed, and the nuclei can occasionally collide.



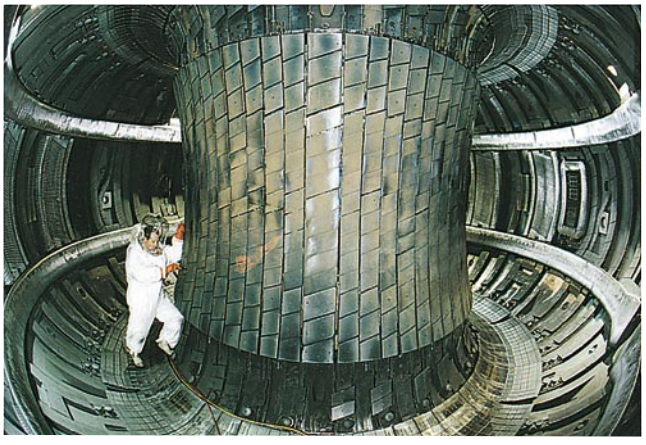

**2 FORMING HELIUM-5**
A deuterium nucleus and tritium nucleus collide and briefly form a nucleus of helium-5. At the same time other short-lived nuclei are also formed.

**3 KEEPING THE HEAT IN**
The helium-5 nucleus sheds a neutron, and gives out radiation. A stable helium-4 nucleus remains. The energy of the neutron and the radiation is absorbed by plasma, or by surrounding matter, and is turned into heat. The plasma must not be cooled by contact with other matter, and is confined within magnetic fields. To work efficiently, this confinement must be sustained long enough for the reaction to give out more energy than has to be put in.



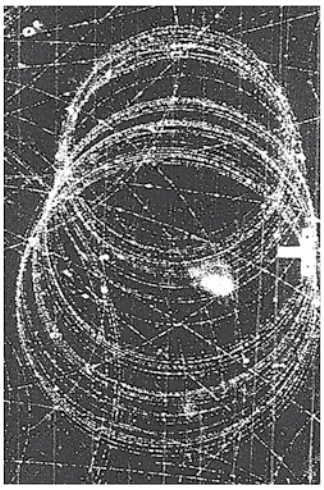

**STAR MAN**
In 1939 Hans Bethe (1906-) was the first scientist to explain how the sun and stars are powered mainly by the fusion of hydrogen into helium. He was also a member of the team that worked on the atomic bomb project.

**A TOUR OF THE TORUS**
The plasma in a fusion reactor circulates in a doughnut-shaped ring, or torus, and is kept at very low pressure. This is the interior of JET, the Joint European Torus, a research fusion reactor operated by 14 countries. Electric current in coils wrapped around the Torus creates a powerful magnetic field that traps the plasma. Bursts of power from the field also heat the plasma. Inside the Torus temperatures can reach as high as 550 million° F (about 300 million° C).



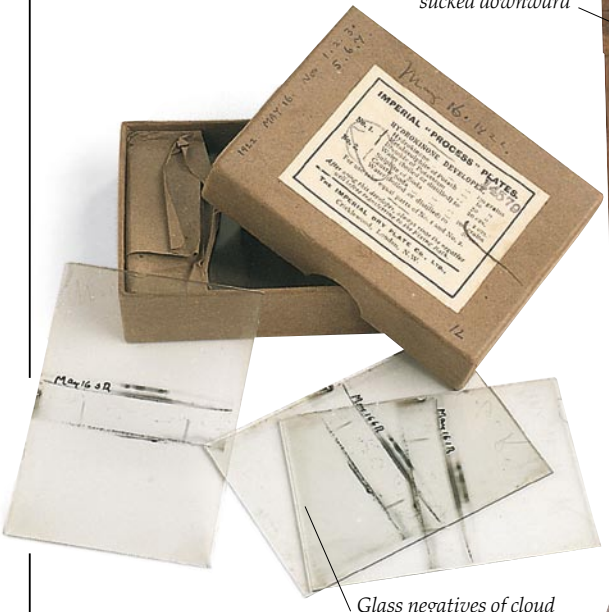
# Subatomic particles

In the early 1930s the atom was thought to be made of three kinds of particle – the proton, neutron, and electron. But soon more particles were found. The existence of the neutrino – a ghostlike particle that "carries away" energy when a neutron decays (p. 53) – was suspected. Then the muon, much like a heavy electron, and the pion, which binds protons and neutrons together in the nucleus, were both discovered in cosmic rays. Accelerators were built to smash particles into nuclei at high speed, creating new particles. Today hundreds of particles are known. They seem to fall into two main classes, hadrons and leptons. Hadrons include the proton and neutron, and are made of pairs or triplets of quarks, which are never seen singly. Leptons, the other class, include electrons and neutrinos.

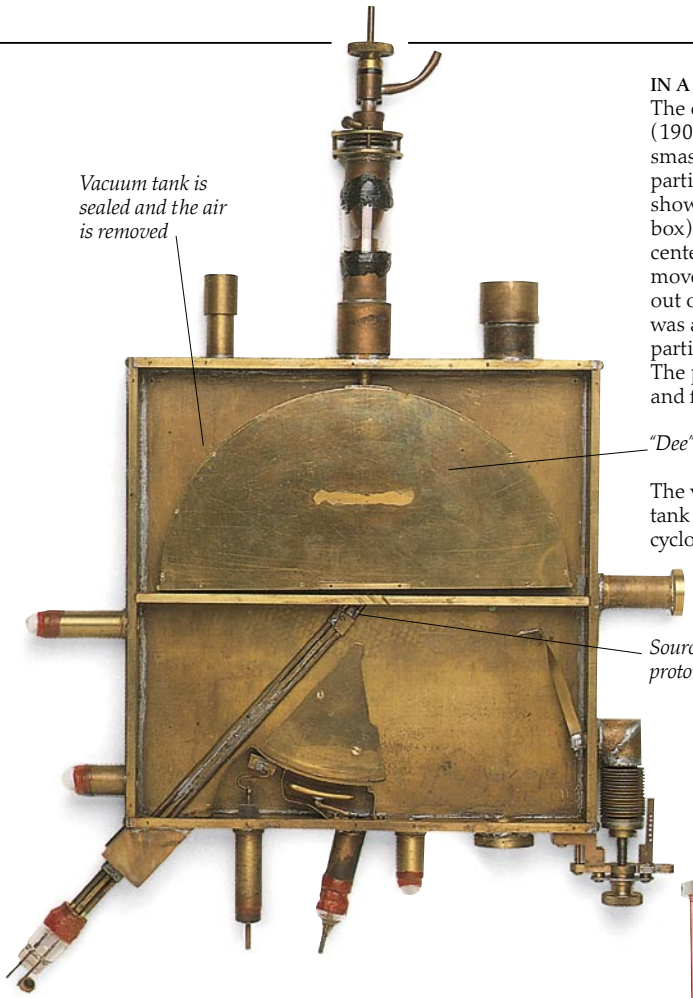


**MAKING TRACKS**
Trails of water droplets in a cloud chamber mark the paths of electrons and positrons (similar to an electron but with a positive charge). Because of their opposite electric charges, they curve in different directions in the chamber's magnetic field. An electron produced near the bottom of the picture circles 36 times before losing its energy.


**AMAZING REVELATIONS**
The cloud chamber, invented by Charles Wilson (1869-1959) in 1911, was the first detector to reveal subatomic particles in flight. Particles from a radioactive source pass through a glass chamber, which contains air and water vapor. In the glass chamber, particles knock electrons out of the atoms in the air, leaving positively charged ions (incomplete atoms). The pressure in the chamber is suddenly reduced, and water vapor condenses on the ions, forming trails of small drops.

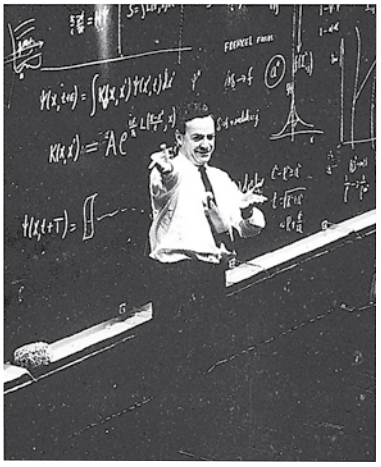



**PARTICLE PICTURES**
Photographic plates of cloud chamber tracks often show particles being created and destroyed. Measuring the tracks can reveal the particles' electric charge, mass, and speed.

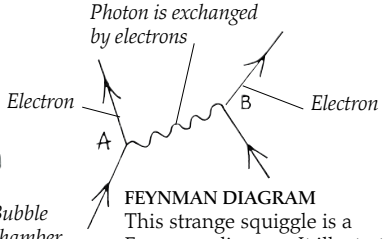



**IN A WHIRL**
The cyclotron, invented by Ernest Lawrence (1901-1958) in 1930, accelerated particles and smashed them into atomic nuclei to form new particles. The vacuum tank of the cyclotron shown here housed a metal "dee" (a D-shaped box). Charged particles entered the dee at the center of the apparatus, and a magnetic field moved them in a small circle, half in and half out of the dee. A rapidly varying electric voltage was applied to the dee, giving a "kick" to a particle whenever it left or reentered the dee. The particle spiraled outward, traveling faster and faster, until it left the cyclotron.

The vacuum tank of the cyclotron

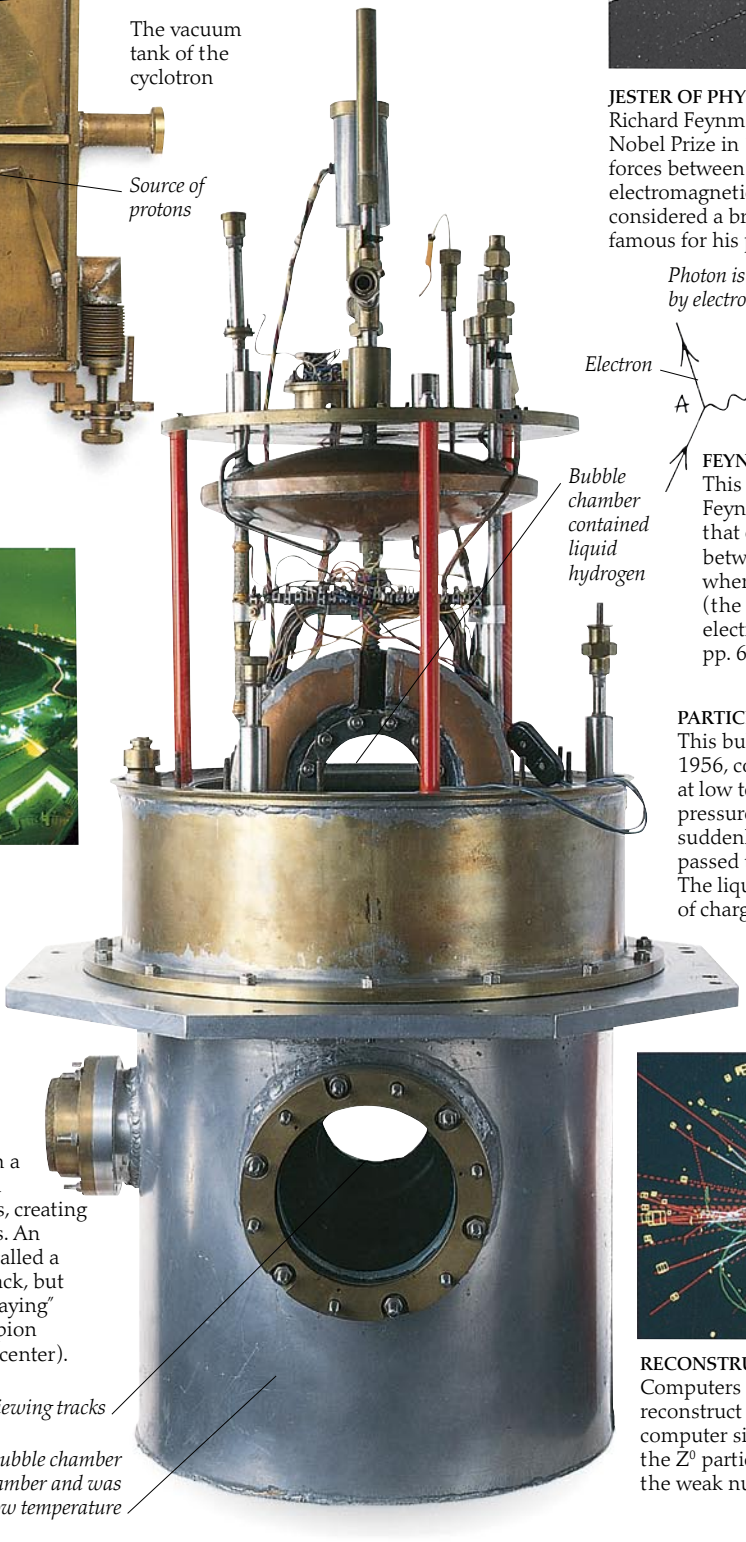


**JESTER OF PHYSICS**
Richard Feynman (1918-1988) shared a Nobel Prize in 1965 for his work on the forces between particles and electromagnetic radiation. He was considered a brilliant teacher and was famous for his practical jokes.

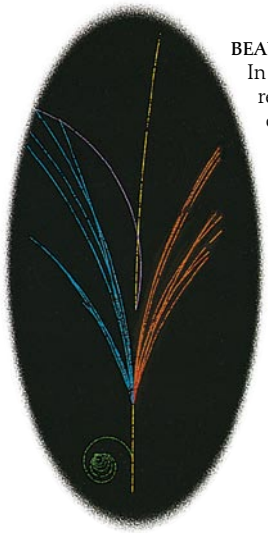



**FEYNMAN DIAGRAM**
This strange squiggle is a Feynman diagram. It illustrates that electromagnetic force between electrons occurs when they exchange a photon (the "carrier" of the electromagnetic force, pp. 60-61).

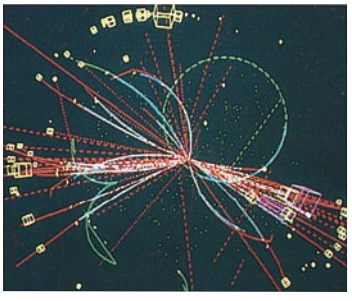
**MAGIC CIRCLE**
The underground Tevatron at the Fermi National Accelerator Laboratory in Illinois has two accelerators, one above the other. The upper one feeds particles to the more powerful lower one.




**PARTICLE FROTH**
This bubble chamber, made in 1956, contained liquid hydrogen at low temperature and high pressure. The pressure was suddenly released, and particles passed through the chamber. The liquid boiled on the trails of charged atoms left by the particles. The trails were photographed, and the chamber was quickly repressurized.



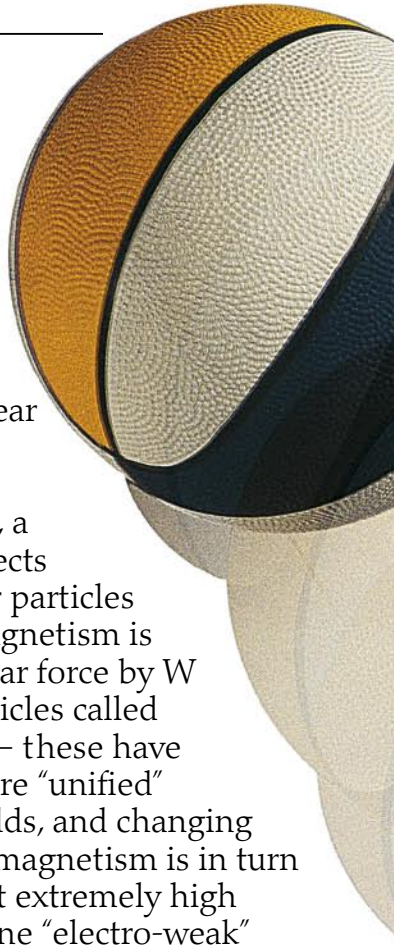
**BEAUTY IN DECAY**
In this computer graphic representation bubble-chamber image, a high-speed proton (yellow, bottom) collides with a proton in a hydrogen atom and disappears, creating a shower of particles. An uncharged particle called a lambda leaves no track, but reveals itself by "decaying" into a proton and a pion (yellow and purple, center).



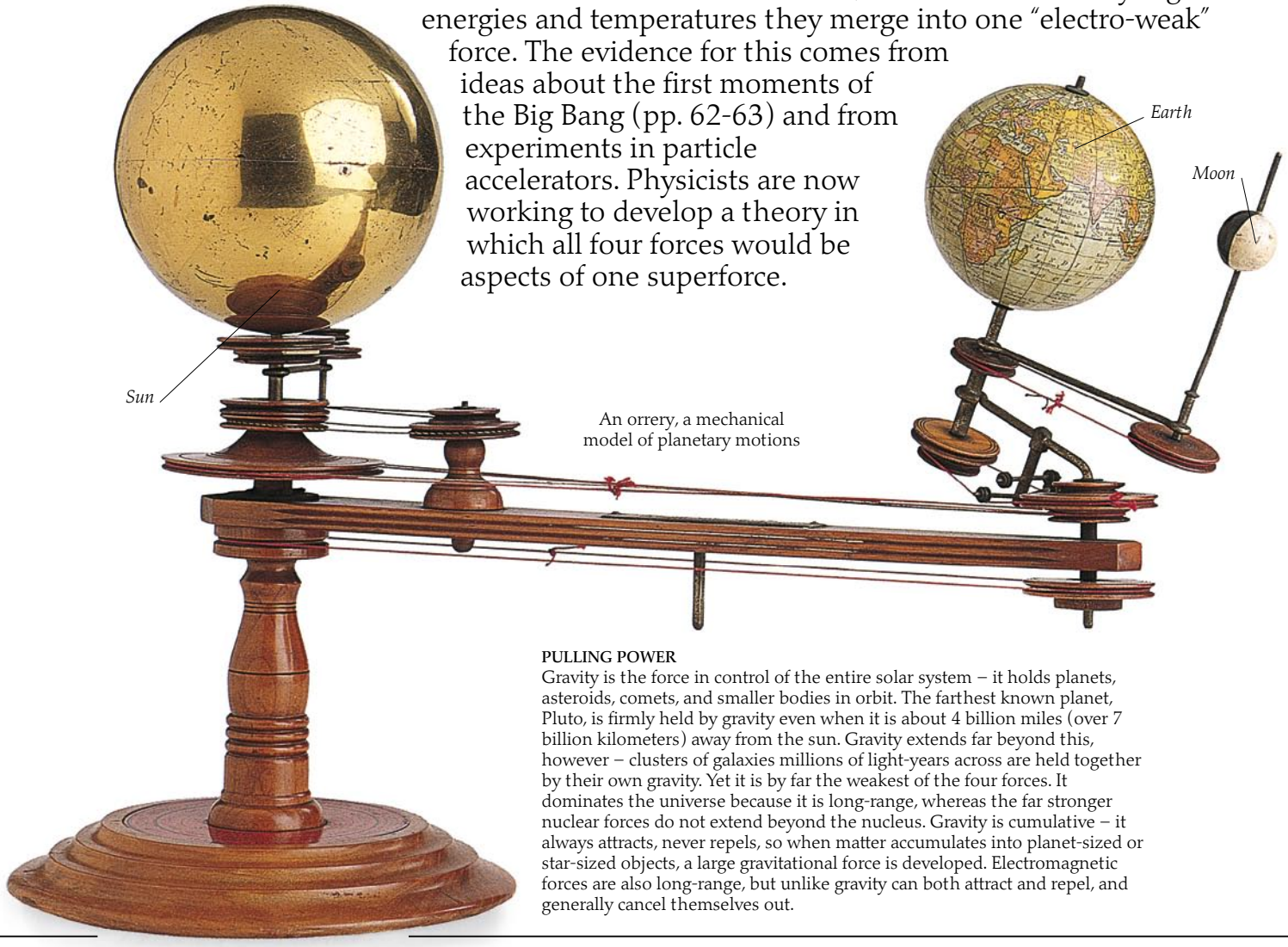
**RECONSTRUCTING THE EVENT**
Computers are now used to reconstruct subatomic events. This is a computer simulation of the decay of the $Z^0$ particle, one of the carriers of the weak nuclear force (pp. 60-61).

# The four forces

**NOT-SO-WEAK FORCE**
The sun is powered by the weak nuclear force, which is responsible for the conversion of hydrogen into helium at the sun's core (p. 57). Under the less extreme conditions on earth, the weak nuclear force is involved in radioactivity. This force does not extend beyond the atomic nucleus and could not be detected until scientists had learned how to probe inside the atom. The particles that carry the weak force, the $W^+$, $W^-$, and $Z^0$, were discovered in 1983 among the debris formed when subatomic particles collided in a giant accelerator.



ALL MATTER IS SUBJECT TO four forces – gravity, electromagnetism, and the weak and strong nuclear forces. Gravity holds people on the earth and the planets in orbit around the sun. Electrons are held in atoms by electromagnetism, a force that is enormously stronger than gravity. The weak nuclear force, a hundred billion times weaker than electromagnetism, is involved in radioactivity and nuclear fusion (pp. 56-57). The strong nuclear force, a hundred times stronger than electromagnetism, affects particles called quarks. Protons, neutrons, and other particles are made up of pairs or triplets of quarks. Electromagnetism is "carried" by particles called photons, the weak nuclear force by W and Z particles, and the strong nuclear force by particles called gluons. Gravity is probably carried by particles, too – these have been dubbed gravitons. Electricity and magnetism are "unified" because electricity in motion produces magnetic fields, and changing magnetic fields produces electrical voltages. Electromagnetism is in turn unified with the weak nuclear force, because at extremely high energies and temperatures they merge into one "electro-weak" force. The evidence for this comes from ideas about the first moments of the Big Bang (pp. 62-63) and from experiments in particle accelerators. Physicists are now working to develop a theory in which all four forces would be aspects of one superforce.




An orrery, a mechanical model of planetary motions

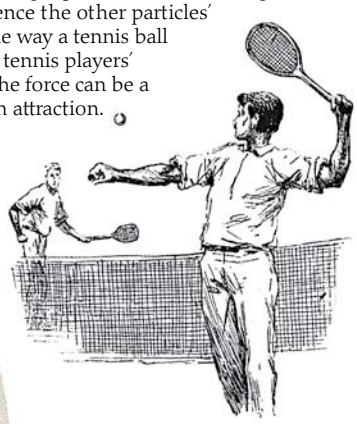
**PULLING POWER**
Gravity is the force in control of the entire solar system – it holds planets, asteroids, comets, and smaller bodies in orbit. The farthest known planet, Pluto, is firmly held by gravity even when it is about 4 billion miles (over 7 billion kilometers) away from the sun. Gravity extends far beyond this, however – clusters of galaxies millions of light-years across are held together by their own gravity. Yet it is by far the weakest of the four forces. It dominates the universe because it is long-range, whereas the far stronger nuclear forces do not extend beyond the nucleus. Gravity is cumulative – it always attracts, never repels, so when matter accumulates into planet-sized or star-sized objects, a large gravitational force is developed. Electromagnetic forces are also long-range, but unlike gravity can both attract and repel, and generally cancel themselves out.

**EVERYDAY INTERACTIONS**
Many forces can be easily seen, such as the way materials hold together and the friction between objects. These are both examples of the electromagnetic force. Gravity is the other force that is most obvious in human life. The electromagnetic force and gravity are shown in the following sequence.

**1 GETTING THINGS GOING**
A ball falls to the floor because the earth's gravity pulls it, but the ball also pulls the earth with exactly the same force. However, since the earth has so much more mass, it does not move visibly, while the ball moves faster and faster. It is described as gaining energy of movement, or kinetic energy. Energy can be defined as making things happen – for example to break things, to make them hotter, and to set them in motion.

**QUARK-FINDER**
The strongest force of all, the strong nuclear force, is felt only by quarks. It binds them tightly together, and they have never yet been observed singly. During the 1980s evidence about the strong force carrying quarks, and the weak force, came from experiments in this giant accelerator, called the Super Proton Synchrotron.

**EXCHANGING MESSAGES**
When two particles are interacting through one of the four fundamental forces, they constantly exchange messenger particles. The messenger particles influence the other particles' movements the way a tennis ball influences the tennis players' movements. The force can be a repulsion or an attraction.



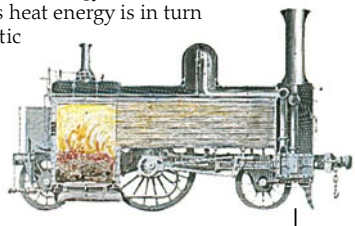
**3 GREAT POTENTIAL**
The potential energy that was momentarily stored in the ball is converted into kinetic energy, and the ball shoots upward. As the ball rises, it loses kinetic energy. If it should fall back to the ground later it will regain its speed. It is therefore described as converting kinetic into potential energy as it rises. In this case the potential energy is associated with height above the ground.

*Gravity pulls the ball to the floor, but the ball pulls the earth with exactly the same force*

*Potential energy is converted into kinetic energy and the ball bounces up*

**2 DOWN WITH A BUMP**
When the ball hits the floor, the force of gravity is opposed by electromagnetism. The electrons in the outer layers of atoms in the ball and the floor repel each other. The upward push of electromagnetism overcomes the downward pull of gravity. The motion is abruptly stopped, but the ball's kinetic energy is converted into other forms. Some is dispersed through the material of the ball and floor as heat. Some is stored as potential energy (energy waiting to be released) in the ball. The electromagnetic forces between the atoms are distorted by the impact, and try to restore the ball to its normal shape. When they succeed the ball regains its kinetic energy.

**CONSTANT QUANTITY**
In any isolated system the total quantity of mass and energy is conserved. In a steam engine, for example, chemical energy of the fuel is converted into heat energy of the fire and of the steam. This heat energy is in turn converted into kinetic energy of the wheels driven by the engine. The total amount of mass and energy is always conserved whichever of the four fundamental forces are involved.

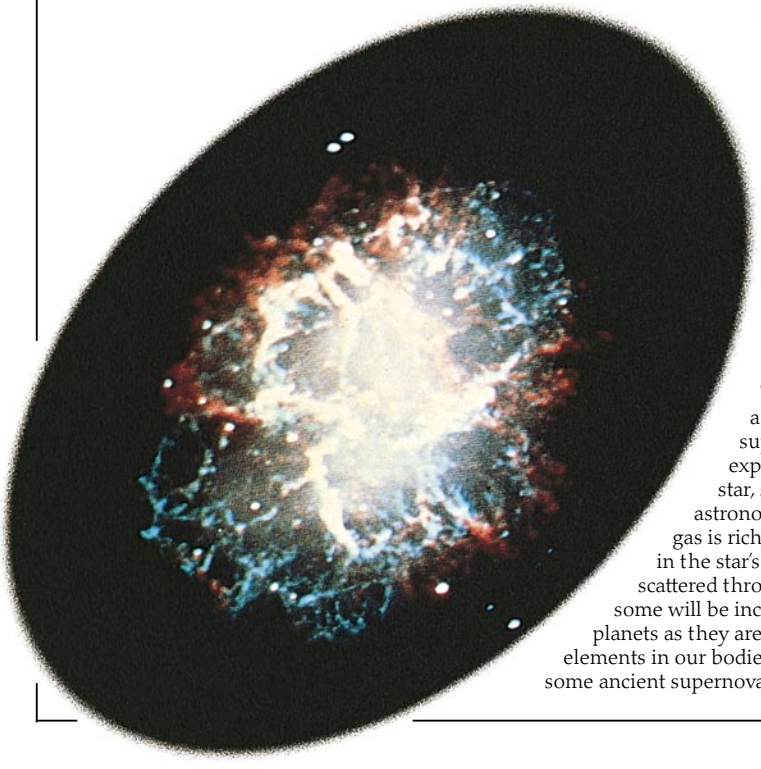


# The birth and death of matter

**VIOLENT UNIVERSE**
Early astronomers thought that the stars were tranquil and unchanging. It is now known, however, that they are born, lead violent lives, and die.

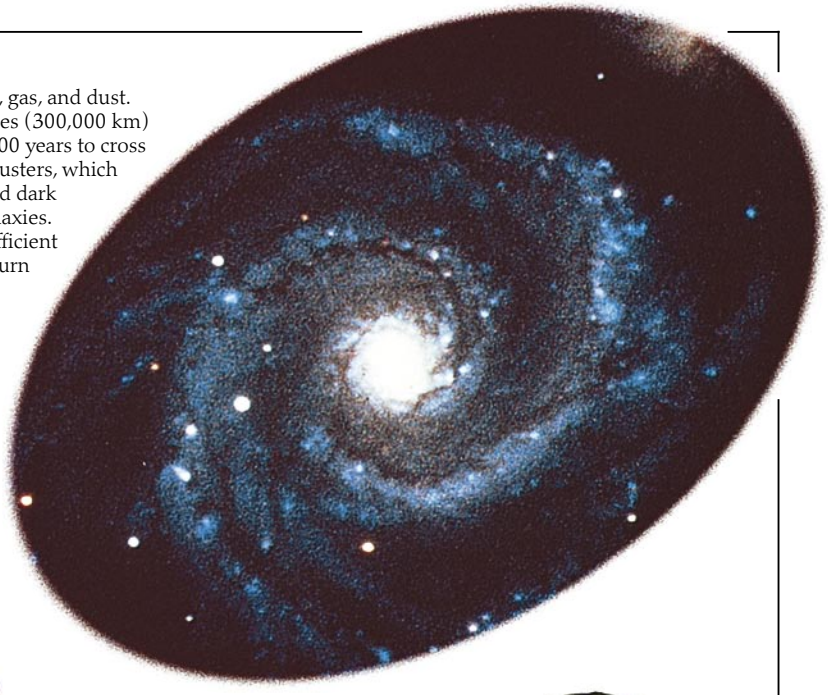
THE TOTAL AMOUNT of mass and energy in the universe never changes. According to a widely held theory, billions of years ago the universe contained matter and energy of extraordinarily high density and temperature, which exploded in the Big Bang. As the gas expanded and cooled, quarks formed protons and neutrons, and some of these built helium nuclei. Eventually complete hydrogen and helium atoms formed. The gas condensed into galaxy-sized clouds which broke up into stars. In the far future, the universe could collapse, be rejuvenated in a new Big Bang, and re-expand, but it is more likely that it will always expand. After the last star has faded, even protons may decay into much lighter particles, and the universe may end as a sea of electrons, neutrinos, and forms of radiation.

**PUTTING THE CLOCK BACK**
Time does not necessarily go forward, or even at the same speed. If the universe were to collapse, it is possible that time could go backward. Time slows down for high-speed objects – a person in orbit for a year ages less (by a hundredth of a second) than people on earth. Even time travel may be possible. In theory, two regions of the universe can be connected by a "wormhole," passing though other dimensions. An object entering one end of a wormhole could reappear from the other end, at an earlier time.

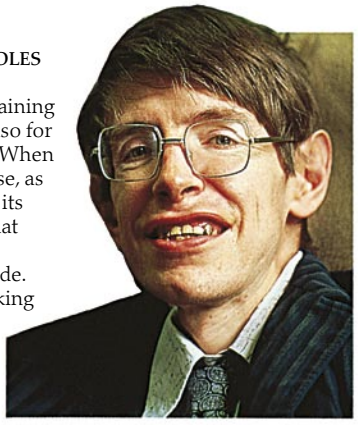



**SCATTERED SEED**
The Crab Nebula is a mass of gas from a supernova – the explosion of a giant star, seen by Chinese astronomers in 1054. The gas is rich in elements made in the star's core. These will be scattered through space and some will be incorporated into new planets as they are born. All the elements in our bodies were made in some ancient supernova.

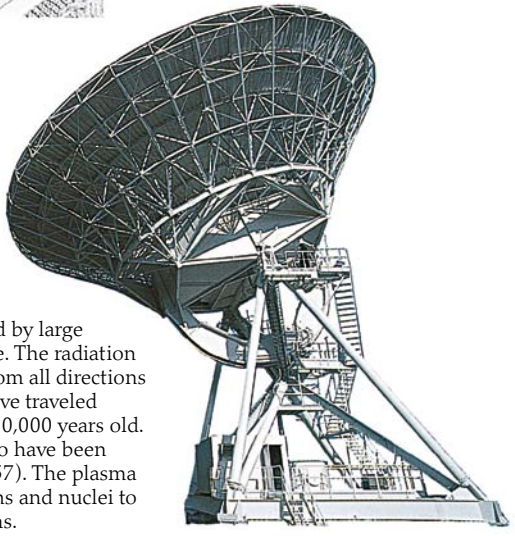
**THE GRAVITY OF DARK MATTER**
Galaxies are huge collections of stars, gas, and dust. Light, travelling at about 200,000 miles (300,000 km) per second, can take as long as 100,000 years to cross a galaxy. Galaxies are grouped into clusters, which hurtle apart. There may be undetected dark matter in the vast spaces between galaxies. The gravity of dark matter may be sufficient to slow the galaxies' expansion and turn it into a collapse.



**A BRIEF HISTORY OF BLACK HOLES**
Stephen Hawking (1942-) is renowned for his work on explaining the birth of the universe and also for his theories about black holes. When matter becomes extremely dense, as in the core of an exploded star, its gravity becomes so powerful that both matter and radiation, including light, are trapped inside. The result is a black hole. Hawking showed that a black hole gives off radiation very slowly. His most popular work is the 1988 book *A Brief History of Time.*



**AN INTELLIGENT UNIVERSE?**
Fred Hoyle (1915-) is associated with the Steady State theory, which holds there was no Big Bang, and matter is always being created throughout space. He claims that some physical laws have been designed by a superior intelligence specifically to produce conditions that make the development of carbon-based life possible.



**BACK TO THE BEGINNING**
So far, the strongest evidence available to scientists for the Big Bang theory is cosmic background radiation. This is microwave radiation that can be detected by large radio telescopes like the one shown here. The radiation always comes with the same strength from all directions in the sky, and is believed by some to have traveled through space since the universe was 100,000 years old. Until this time the universe is thought to have been made of hot expanding plasma (pp. 56-57). The plasma then cooled sufficiently to allow electrons and nuclei to join up and form the first complete atoms.

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