The States of Matter

For Grades 6-8

This Pack contains:

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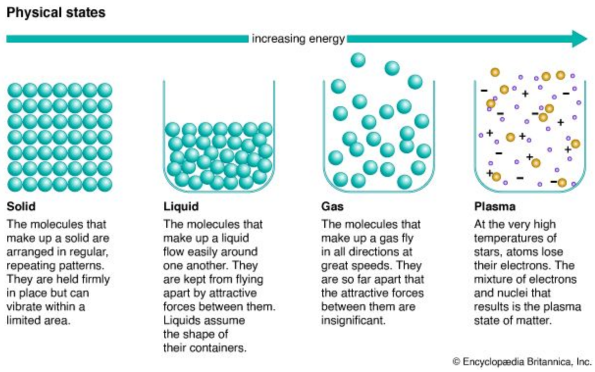
ARTICLE

matter

Britannica Note:

The section "The States of Matter" discusses the four states of matter in the context of atomic theory.

An electron, a grain of sand, an elephant, and a giant quasar at the edge of the visible universe all have one thing in common—they are composed of matter. Matter is the material substance that makes up the physical universe. A beam of light, the motion of a falling stone, and the explosion of a stick of dynamite all have one thing in common—they are expressions of energy. Energy and matter together form the basis for all observable phenomena.



Physical states of matter.

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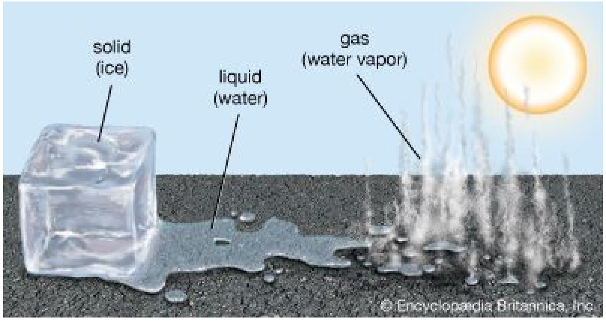
The States of Matter



The three principle states of matter are solid, liquid, and gas. Water exists in these states—as ice (solid), liquid water, and water vapor (gas). Like all gases, water vapor is invisible; it is shown here merely for the purpose of illustration.

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Most of the matter that people ordinarily observe can be classified into one of three states, or phases: solid, liquid, or gas. Solid matter generally possesses and retains a definite size and shape, no matter where it is situated. A pencil, for example, does not change in size or shape if it is moved from a desktop and placed upright in a glass. A liquid, unlike a solid, assumes the shape of its container, even though, like a solid, it has a definite size, or volume. A pint of water changes its shape when it is poured from a glass into a bowl, but its volume remains the same. A gas expands to fill the complete volume of its container.

At a given temperature and pressure, a substance will be in the solid, liquid, or gaseous state. But if the temperature or the pressure changes, its state may also change. At constant atmospheric pressure the state of water, for example, changes with changes in temperature. Ice is water in the solid state. If it is removed from a freezer and placed in a warm pan, the ice warms up and changes to the liquid—water. If the pan is then placed over a hot fire, the water heats up and changes to water vapor, the gaseous state of water.

Most substances can exist in any of the three states (provided that they do not decompose chemically, as sugar, for example, often does when it is heated in air). Oxygen must be cooled to very low temperatures before it becomes a liquid or a solid (*see*cryogenics). Quartz must be heated to very high temperatures before it becomes a liquid or a gas.

In most people's experience, wide changes in pressure are not as common as drastic changes in temperature. For this reason, examples of the effects of pressure on the states of matter are not common. Often, high-pressure machines and vacuum (low-pressure) machines must be used to study the effects of pressure changes on matter. Under very low pressures, matter generally tends to enter the gaseous phase. At very high pressures gases tend to liquefy and liquids tend to solidify. In fact, at the very lowest temperatures that can be reached, helium will not solidify unless a pressure of some 25 times normal atmospheric pressure is applied.

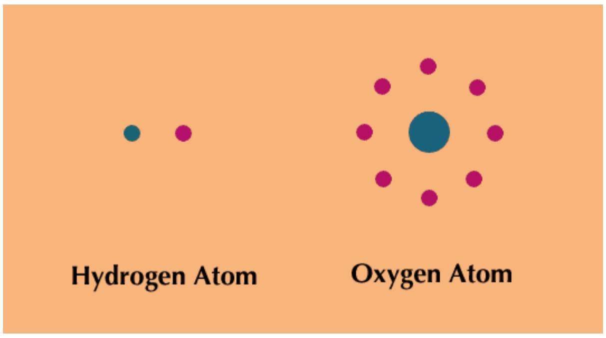
The relation between pressure and temperature in changes of state is familiar to people who live at high altitudes. There the pressure is lower than at sea level, so water boils at a lower temperature. Cooking anything in water takes longer on a mountaintop than at sea level.

These properties of the three states of matter are easily observed. They are explained, however, by a theory that describes the behavior of particles far too small to be seen.

Atomic Theory of Matter

All substances are made up of tiny units called atoms. Each atom consists of a massive, positively charged center called the nucleus, around which fly one or more negatively charged electrons.

The nucleus itself contains at least one proton, a positively charged particle. In all atoms except those of ordinary hydrogen, the nucleus also contains at least one neutron, a particle that has no electrical charge. A neutral atom has the same number of electrons as protons, so the electrical charges cancel.



One electron (pink) circles the lone proton (blue) in a hydrogen atom. An oxygen atom has eight protons (blue) which can bind eight electrons.

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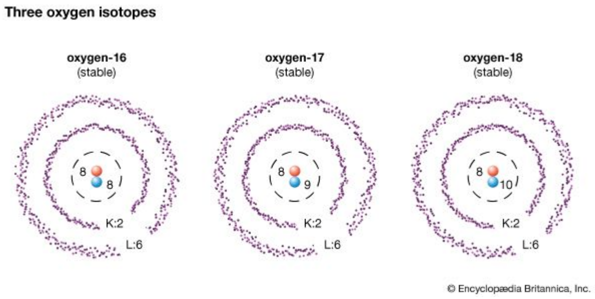
The identity of an atom and its atomic number is determined by the number of protons in its nucleus. For example, there is one proton in the nucleus of a hydrogen atom, so hydrogen has atomic number 1. Oxygen, with eight protons, has atomic number 8; mercury has atomic number 80; and uranium has atomic number 92.

Substances that are composed of only one kind of atom are called elements. Only 92 elements occur naturally on Earth in significant amounts. The lightest is hydrogen; the heaviest is uranium.



A diagram represents the nuclei of three oxygen isotopes. Each nucleus has eight protons (gray) and eight, nine, or 10 neutrons (green).

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The nuclei of a given element all have the same number of protons but may have a differing number of neutrons. For example, about 99.8 percent of the oxygen nuclei in nature contain eight neutrons as well as eight protons. But a very few oxygen nuclei contain nine neutrons, and some even contain 10 neutrons. Each kind of nucleus is a different isotope of oxygen. Each isotope has a different number of neutrons.

Most hydrogen atoms are made up of a single proton with an electron circling it. However, one isotope of hydrogen contains a neutron as well. This isotope is called deuterium. Because neutrons have approximately the same mass as protons, deuterium atoms have about twice as much mass as those of the ordinary isotope of hydrogen. An extremely rare form of hydrogen, called tritium, has one proton and two neutrons in its nucleus. This is an unstable arrangement, so the tritium nucleus is radioactive. Over time it gives off a negatively charged particle and changes to a stable helium nucleus with two protons and one neutron.

Many other isotopes of the various elements are radioactive. They can give off radiation of different kinds, changing to other elements or to different isotopes of the same element. Many radioactive isotopes are man-made, produced in nuclear reactors and particle accelerators.

In addition to the 92 naturally occurring elements, scientists have synthesized more than two dozen others. (Two of these synthesized elements were later found to exist in nature but only in trace amounts.) They are called the transuranium elements because they are all made of atoms that have more mass than the uranium atom. All transuranium elements, therefore, have atomic numbers greater than 92. All of these elements are unstable and decay radioactively; many of them exist for only a fraction of a second.

Substances that are composed of more than one kind of atom are either compounds or mixtures. The atoms in compounds are joined together chemically. In one type of compound, ions (electrically charged atoms or groups of atoms) are held together; in another type of compound, atoms are joined together to form molecules. This chemical bonding is the result of the electrical forces between the ions or the force of attraction of the electrons of one atom for the nucleus of another atom. For example, in one type of bonding two atoms of hydrogen and one atom of oxygen share electrons and form a water molecule. The chemical symbol for water, H_2O, denotes this combination (*see*chemistry).

The atoms, ions, or molecules in a mixture intermingle with one another but are not joined chemically. Salt water is a kind of mixture called a solution. Salt is composed of ions, and they spread throughout the water when the salt dissolves.

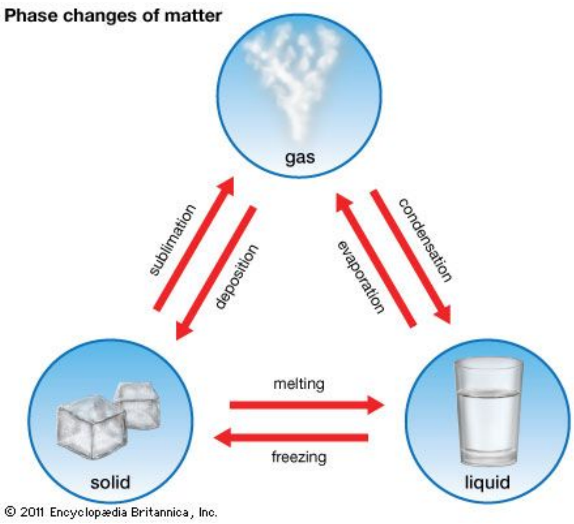
Regardless of whether water is in the solid, liquid, or gaseous state, its molecules always consist of one atom of oxygen and two atoms of hydrogen. Solid water, liquid water, and gaseous water all have the same chemical composition. Instead, the difference between these physical states depends on which energy is larger: the energy associated with the attraction between molecules or the heat energy.

Atomic Theory and the States of Matter

A certain amount of attraction exists between all molecules. If repulsive forces are weaker than these intermolecular attractive forces, the molecules stick together. However, molecules are in constant random motion because of their thermal, or heat, energy. As the temperature of a substance increases, this molecular motion becomes greater. The molecules spread out and are less likely to unite. As the temperature decreases, the motion becomes smaller. The molecules are thus more likely to linger in each other’s vicinity and bind together.

In a solid, the intermolecular attractive forces overcome the disruptive thermal energies of the molecules. In most solids the molecules are bound together in a rigid, orderly arrangement called a crystal. These types of solids are called crystalline solids. (In some other solids, such as glasses, gels, and many plastics, the molecules are not arranged in crystals.) Although the molecules in a crystal are held rigidly in place, they still vibrate because of their thermal energy. It may be difficult to think of ice as having heat energy. But even in ice each water molecule, though held firmly in the crystal pattern, vibrates around a fixed position. This vibrational motion is an expression of the thermal energy of ice.

As the temperature of the solid is increased, its molecules vibrate with greater and greater energies until they gain enough vibrational energy to overcome the intermolecular attractive forces. They then break loose from their fixed positions in the crystal arrangement and move about more or less freely. The substance now assumes the shape of its container but maintains a constant volume. In other words, the substance has melted and is now a liquid.



The phase changes of matter include melting, freezing, evaporation, condensation, deposition, and sublimation.

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Melting is a change of state, or a phase change. The temperature at which melting takes place varies from substance to substance. Water and iron, for example, melt at different temperatures. The melting temperature is the same, however, for a given material at a given pressure. At atmospheric pressure water always melts at 32° F (0° C).

Phase changes can work in reverse. If the temperature of a liquid is gradually decreased, a point is eventually reached at which the intermolecular forces are strong enough to bind the molecules despite the disruptive thermal motions. Then a crystal forms: the substance has frozen. The temperature at which this liquid-to-solid phase change takes place is the freezing point. The freezing point of a substance occurs at the same temperature as its melting point.

This theory of matter can also explain the liquid-to-gas change of state, a process called vaporization or evaporation. As heat is applied to a liquid, some molecules gain sufficient thermal energy to overcome the intermolecular attraction—surface tension—exerted by molecules at the surface of the liquid. These high-energy molecules break free from the liquid and move away. Such molecules are now in the gaseous state. As more heat is applied, more molecules gain enough energy to move away until—at a temperature called the boiling point of the liquid—all the molecules can gain enough energy to escape from the liquid state.

The average distance between molecules in the gaseous state is extremely large compared to the size of the molecules, so the intermolecular forces in a gas are quite weak. This explains why a gas fills the entire volume of its container. Since intermolecular forces are so small, a gas molecule moves until it strikes either another gas molecule or the container wall. The net effect of the many molecules striking the container walls is observed as pressure.

Sometimes a substance will pass directly from the solid state to the gaseous state without passing through the liquid state. This process is called sublimation. Dry ice (solid carbon dioxide) sublimates at atmospheric pressure. Liquid carbon dioxide can form if the gas is subjected to over five times atmospheric pressure.

The Fourth State of Matter

At extremely high temperatures atoms may collide with such force that electrons are knocked free from the nuclei. The resulting mixture of free negative and positive particles is not a gas according to the usual definition. Such material is called a plasma. Some scientists consider the plasma state to be a fourth state of matter. Actually, about 99 percent of the known matter in the universe is in the plasma state. In stars matter is hot enough, and in interstellar space it is diffuse enough, for the electrons to be completely separated from the nuclei. From an astronomical standpoint, somewhat unusual conditions exist on Earth, where plasmas are difficult to produce.

Inertia and Gravitation

Another way of approaching the subject of matter is on the basis of the concepts of inertia and gravitation. Matter can be defined as anything that has inertia and that experiences an attractive force when in a gravitational field.

Inertia

Isaac Newton's first law of motion describes inertia. A body at rest tends to remain at rest; a body in motion tends to keep on moving at the same speed and in a straight line. In order to move a resting body or to stop a moving body, some effort, called a force, is required. The tendency of a body to remain at rest or, once moving, to remain in motion is inertia.

The inertia of a body is related to its mass. More massive bodies possess greater inertia than less massive bodies. A body's mass can be measured by exerting a force on the body and observing the acceleration that results. Newton's second law of motion states that the mass (m) is equal to the force (F) divided by the acceleration (a): $m = F/a$.

In principle, this measurement can be made anywhere in the universe. Wherever the experiment is performed, the same force applied to the same body produces the same acceleration. The mass of a body is, therefore, the same everywhere. (According to relativity, a moving body's mass actually increases with its speed, as will be discussed below. However, at all but extremely high speeds—those approaching the speed of light—this change in mass is too tiny to be observed.)

Gravitation

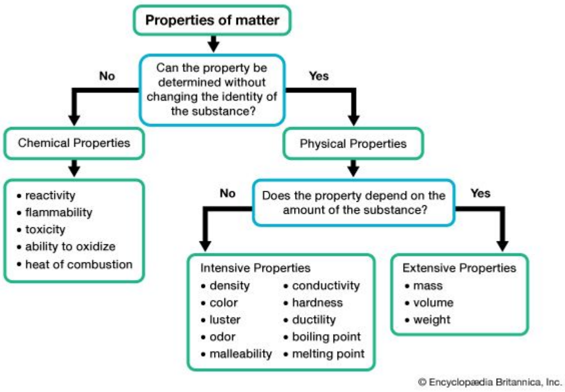
All matter exerts a gravitational attractive force on other matter. The gravitational force is weak compared to the three other known forces—the electromagnetic force, the strong force (which holds the nucleus of an atom together), and the weak force (which is involved in some forms of radioactivity). The magnetic force of a small magnet, for example, can hold up a pin against the gravitational pull of the entire Earth. However, on the scale of everyday objects near Earth or that of astronomical bodies, the gravitational force is the dominant one of the four known forces. The fall of bodies released from a height to the surface of Earth is the most familiar example of gravitation. Earth's orbit around the Sun and the motion of the Sun are also results of the force of gravitation.

The weight of a body is determined by the gravitational forces exerted upon it. A body at Earth's surface experiences a gravitational pull toward the center of the planet. If the body moves farther from Earth's center (to the top of a high mountain, for example), the gravitational force on it decreases, so its weight decreases. If the body moves to a lower point on Earth's surface (into a deep valley, for example), the gravitational force on it increases, so its weight increases. The increase is far greater if the body then moves to the gravitational field of a giant planet, say, Jupiter. A body's weight can change; it varies with the strength of the gravitational field in which the body is placed.

It is important to understand the difference between mass and weight. While the mass of a body is the same everywhere, the weight of a body depends upon the strength of the local gravitational field. An astronaut standing on the surface of the Moon weighs less than he does when standing on Earth, but his mass is the same in both places.

However, there is a relationship between mass and weight. Mass and weight are proportional to each other. The more mass a body has, the more it will weigh at any given point in space.

Properties of Matter



Matter can be identified and described by various characteristics. The flowchart shows how to determine if such characteristics are chemical or physical properties. Physical properties can be further divided into intensive and extensive properties.

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Matter can be identified and described on the basis of characteristics called properties. The properties of matter can be grouped into two main categories: physical and chemical.

Physical Properties

Physical properties are characteristics that can be observed or measured without changing the composition of a substance. Mass and volume are examples of physical properties. Measuring the mass or volume of a substance does not change its composition. If a cube of pure iron with a mass of 300 grams was broken into three 100-gram pieces, each smaller piece would still be composed of iron atoms.

Physical properties of metals and nonmetals

property	metal	nonmetal
hardness	hard	soft
density	high	low
luster	shiny	dull
ductile (can be stretched into a wire)	yes	no
malleable (can be beaten into sheets)	yes	no
thermal conductivity	good conductor	poor conductor
electrical conductivity	good conductor	poor conductor
sonorous (rings when struck with hammer)	yes	no

Metals and nonmetals have different physical properties.

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Some physical properties are specific for a given substance and can be used to help identify it. These include color, odor, texture, hardness, density, and thermal and electrical conductivity. Most metals, for example, have a high density (a high mass per unit volume). Thermal and electrical conductivity—the ability to conduct heat and electricity—are key physical properties of metals and in fact help distinguish them from nonmetals. Hardness, or how resistant a substance is to scratching, is one of several physical properties used to identify minerals.

Melting point and boiling point are fundamental physical properties of all matter. The melting point of a substance is the temperature at which it changes from a solid to a liquid. Ice (the solid form of water) melts, or changes from a solid to a liquid, at 32 °F (0 °C). The temperature at which a substance changes from a liquid to a gas is its boiling point. The boiling point of water—the temperature at which liquid water changes to water vapor—is 212 °F (100 °C).

Both melting point and boiling point are properties that indicate a change of the state of matter but not of its composition. A change of state is an example of a physical change; it changes the physical properties of a substance but not its composition. Whether water is in a solid, liquid, or gaseous form, it is still composed of two hydrogen atoms and one oxygen atom.

Chemical Properties

The chemical properties of matter are those characteristics that give it the ability (or inability) to undergo a chemical change—a change in composition. The chemical properties of a substance predict whether a chemical reaction will or will not take place.

Combustibility (how readily a substance can burn) is an example of a chemical property. For example, wood burns readily, forming ash and smoke. The chemical components of wood are also in the ash and smoke that are formed, but they are arranged differently. Since the composition of the wood has been altered, it has undergone a chemical change.

Another chemical property is corrosion, or the ability to rust or tarnish, is another chemical property. When iron is exposed to water, it undergoes a chemical reaction with the oxygen atoms in water, forming a new substance called iron oxide, or rust. Iron oxide contains iron atoms and oxygen atoms and thus has a different composition than either iron (which contains only iron atoms) or water (which contains hydrogen and oxygen atoms).

Modern Theories of Matter

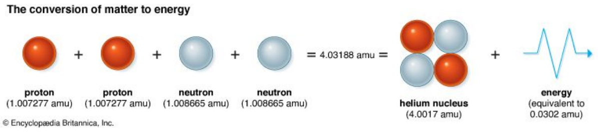
Equivalence of Matter and Energy

Albert Einstein’s theory of special relativity, which considers matter and energy equivalent, greatly extended scientists’ understanding of matter. This theory states that anything having energy has mass and that the amount of a body’s mass (*m*) is related to the amount of its energy (*E*). The exact relationship is given by Einstein’s famous equation, $E = mc^2$, where *c* is the speed of light—186,300 miles per second (3×10^8 meters per second).

Scientists had been accustomed to viewing matter and energy as two separate quantities of the universe. But the theory of special relativity relates the two. According to this theory, an object’s mass varies as its speed changes. An object traveling at a high velocity will have a greater mass than the same object traveling at a low velocity. The smallest mass a body can have is the mass it has when it is at rest. This minimum mass is called the body’s rest mass, and it never changes.

Even at speeds that are ordinarily regarded as quite high—the speed of a jet aircraft, for example—the increase in mass from the rest mass is too small to detect. But in high-energy particle accelerators, when a particle travels at speeds near the speed of light, the mass of the particle increases observably.

Centuries of experiments had also led scientists to believe that the amount of matter in the universe never changes. They expressed this concept as the law of the conservation of mass: matter can neither be created nor destroyed. Similar to this law is the law of the conservation of energy, which states that energy can neither be created nor destroyed. One reason Einstein’s theory of relativity was so hard to accept was that it said these laws were wrong, that energy can be converted to matter and that matter can be converted to energy. Experimental observations have since confirmed this fact.



The sum of masses of two protons and two neutrons is 4.03188 atomic mass units (amu). When they are joined in a helium nucleus, their mass is 0.0302 amu smaller. The difference has been converted into energy. The helium nucleus is very stable.

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The conversion of matter to energy can be demonstrated in nuclear reactions. The masses of individual protons and neutrons are frequently measured in atomic mass units (amu). One amu is $^{1}/_{12}$ of the mass of an atom of carbon-12 (the most common form of carbon). The mass of a free proton is 1.007277 amu. The mass of a free neutron is slightly larger: 1.008665 amu. When two protons and two neutrons join to form a helium nucleus, one might expect that the mass of the helium nucleus would be equal to the sum of the masses of two protons and two neutrons, or 4.0319 amu. But experiments show that a helium nucleus has a mass of 4.0017 amu, or 0.0302 less than their sum. Scientists theorized that the missing 0.0302 amu had been converted to energy.

The helium nucleus has less energy than its isolated components. That energy difference contributes to the stability of the helium nucleus and is called its binding energy. The exact amount of energy that was given up in forming the helium nucleus must be supplied to break it up, that is, to overcome the binding energy. Scientists have learned how to convert between values for mass and values for energy. Thus, 1 amu is equal to 931 MeV (million electron volts), or 1.49×10^{-3} ergs.

Matter changes to energy in chemical reactions, when atoms or molecules are formed, as well as in nuclear reactions. For example, when a hydrogen atom is formed by the combination of a proton and an electron, the mass of the resulting hydrogen atom is less than the sum of the masses of the isolated electron and proton. In this case, however, the mass lost is tiny—only about 2.4×10^{-32} grams, or 1.5×10^{-8} amu. For this reason, the loss of matter during chemical reactions is not observed.

Experiments have convinced scientists that mass and energy are equivalent and interchangeable. The laws of the conservation of mass and the conservation of energy have therefore been combined into a single law, the law of the conservation of mass-energy. This states that the sum of the mass and the energy in the universe is a constant. Transformations between mass and energy are governed by the equation $E = mc^2$.

The Mass of Radiation

Like all types of electromagnetic radiation, light is a form of energy. At the beginning of the 20th century, light was thought to consist of electromagnetic waves. But in 1905 Einstein pointed out that light often behaves as if it were made up of particles rather than waves. For example, in the photoelectric effect, light behaves as if a series of light particles strikes the electrons of a metal. Such particles of electromagnetic radiation are called photons.

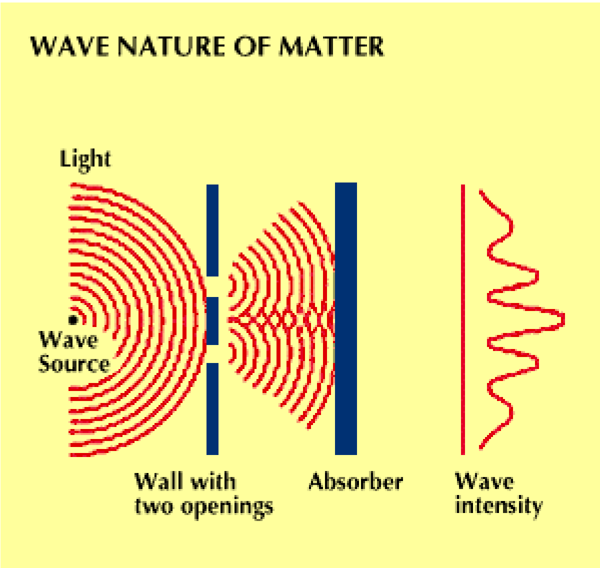
According to the theory of relativity, since light has energy, it should also have mass. Although a photon has a mass of zero when (theoretically) at rest, the mass of a moving photon can be calculated from Einstein’s equation. It is very small, around 10^{-33} grams for a photon of visible light. But if light has mass, it should respond to gravitational forces. Indeed, when light from a star must pass near the Sun to reach Earth, the beam deviates from the straight path that it follows when the Sun is not between the star and Earth. This is believed to happen because the Sun’s huge gravitational field attracts the mass of the light photons strongly enough to bend the beam. The effect is very small, which is why a body as massive as the Sun is needed to observe it.

This development presented a great dilemma, for it seemed to indicate that light behaves as a particle. However, it had long been known that light produces what are called diffraction and interference patterns, which are exclusively characteristic of waves. Was light, then, to be considered a wave or a particle?

The answer is both, according to modern physics. The particle aspects and the wave aspects of light complement each other. Both are necessary for a complete understanding of light. However, it is impossible to measure both the particle and wave aspects of light at the same time. Which of the two aspects is observed depends on the particular phenomenon that is being studied. Diffraction is an example of wave behavior, while the photoelectric effect is an example of particle behavior.

Wave Properties of Matter

In 1923, about two decades after the discovery that what had been regarded as waves exhibited properties of particles, Louis de Broglie advanced the hypothesis that the converse might also be true. He theorized that what had been regarded as particles might exhibit the properties of waves. Four years later “matter waves” were actually observed.



This experiment shows a device that will produce light waves. Beyond the wave source is a wall with two slits, and beyond that is an absorber to prevent reflected waves. As the light waves go through the two slits, two new series of waves are created, each having one of the slits as its center. As these secondary waves spread out in the region between the wall and the absorber, they meet and interfere with each other. At some points the two waves are exactly in phase so that their intensity is doubled. At other points they are exactly out of phase and cancel each other out. At most points the waves are somewhere between the two extremes.The intensity of the waves as they hit the absorber varies along the length of the absorber, depending on the amount of interference between the waves as they hit. A maximum intensity occurs at the center of the apparatus, since the waves are exactly in phase there. On either side of this intensity peak, the intensity decreases and increases as the waves go in and out of phase. The observed intensity pattern, shown at the right of the diagram, is a typical interference pattern, strictly a wave phenomenon.
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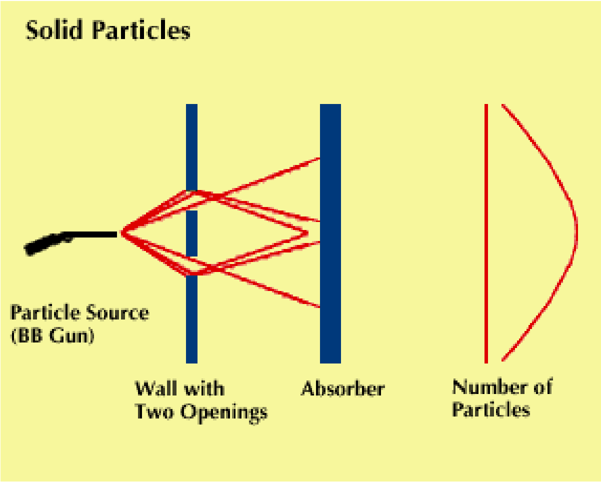

In this experiment, a BB gun shoots BB's rather erratically toward a similar double-slit arrangement. The slits are just wide enough to admit a BB on a direct path from the source. But a BB that reaches one of the slits may also pass through by bouncing off the edges. Six possible paths are shown in the diagram, but many more can occur to fill up the space between the hits in the middle and the hits at the edges. To the right of the diagram a curve shows the distribution of BB's that occurs when they are fired randomly. The maximum at the center of the apparatus falls toward either edge. There is no interference in this typical particle distribution pattern.

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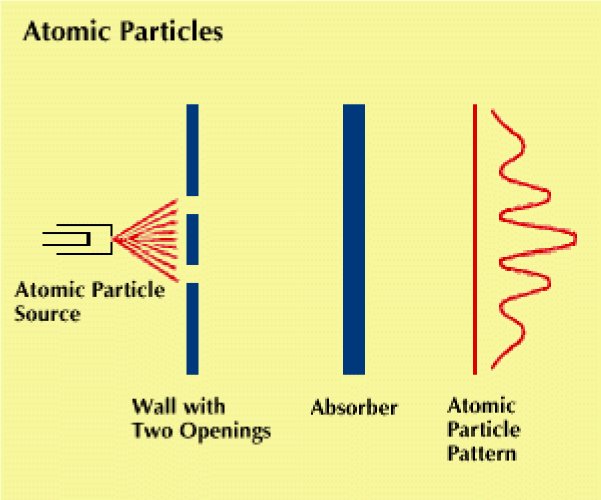

Electrons are shot through the double slit. Here, however, the slits are much narrower—so narrow that gaps between atoms in crystals must be used. If electrons acted like particles, the resulting electron distribution would be like that of the BB's. However, the observed pattern is like the one associated with wave phenomena. In this experiment the electrons exhibit wavelike behavior. (In actual experiments the pattern is more complicated than shown here.)

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Beams of electrons were aimed at crystals, and their patterns of deflection and scattering were observed. These patterns looked as if they had been formed by the deflection of waves, supporting the theory that electrons could act like waves. In other experiments, diffraction patterns were observed. Like light, matter has properties of both particles and waves.

Electron waves are used to great advantage in the electron microscope. Because the waves are much shorter than light waves or even ultraviolet waves, the electron microscope has a much greater resolving power than light microscopes. Electron microscopes show much more detail than do light microscopes.

The Building Blocks of Matter

All matter is made up of elementaryparticles. Atoms are not elementary particles since they are themselves composed of smaller particles—electrons, protons, and neutrons. Some particles, such as photons, commonly exist apart from atoms.

As scientists developed methods for studying radioactive particles, for breaking atoms apart, and for detecting particles from space (cosmic rays), they concluded that there must exist other particles in addition to the photon, electron, proton, and neutron. In the early 1930s Wolfgang Pauli and Enrico Fermi postulated the neutrino, a particle with no charge and either very little or no mass, which interacts much more weakly with matter than a photon does. They held that only the existence of such a particle could account for the energy and momentum that is lost when a neutron in a nucleus decays into a proton and a free electron, a process called beta decay. Particles with the characteristics postulated by Pauli and Fermi were very difficult to detect, but experiments performed in 1956 confirmed their existence.

Since then, hundreds of different particles have been detected as a result of collisions produced in cosmic-ray reactions and particle-accelerator experiments. They are called subatomic particles because they are smaller than an atom. Most of these particles are highly unstable, existing for less than a millionth of a second. There are three different types of subatomic particle: leptons, quarks, and bosons. Leptons and quarks together form atoms, so they are considered the basic building blocks of matter. The six known types of leptons are the electron, the muon, the tau, and the three types of neutrino. There are also six types of quark. Quarks make up neutrons and protons. Bosons include the photon (seen as light), the graviton, and the gluon. The graviton is a theoretical particle that has not yet been discovered. If it exists, the graviton carries the gravitational force, just as the photon carries the electromagnetic force and the gluon carries the strong force.

Antimatter

In 1928 P.A.M. Dirac claimed that a particle of the same mass as an electron but having a positive charge could exist. Four years later a positive electron, or positron, was detected. This was the first experimental evidence for the existence of antimatter. If a particle possesses an electrical charge, its antiparticle possesses an equal but opposite charge. Many other kinds of antimatter particles have since been discovered. Particle physicists now assume that for every subatomic particle that occurs in nature a corresponding antiparticle exists, even if the antiparticle has not been observed. An antiparticle may be discovered years after its corresponding particle. Scientists have also created antiatoms, which are made up of antiparticles.

An important property of matter is demonstrated when an electron and a positron meet. They annihilate one another. Both particles disappear. The law of conservation of mass-energy states that if mass is destroyed an equivalent amount of energy must be created, so that the sum of mass-energy before and after annihilation are exactly equal.

This is precisely what happens. When an electron and a positron annihilate each other, a large amount of energy, corresponding to the mass of the two particles, is always given off. Similar annihilations occur when other particles meet their antiparticles.

A converse to the process of particle-antiparticle annihilation is known as pair production, in which radiation disappears and matter is created. The most common example is the creation of an electron-positron pair from a photon. For this to occur, a minimum photon energy, corresponding to two electron masses, is necessary.

The Milky Way galaxy, to which Earth belongs, is apparently composed primarily of particles rather than antiparticles. It obviously cannot be made up of equal amounts of particles and antiparticles, for if it were there would be a cataclysmic annihilation and the matter in the galaxy would be converted to radiation. There is also no evidence that other galaxies in the universe are composed primarily of antiparticles. Matter apparently dominates antimatter in the universe.

String Theory

Relativity is essential for studying the universe on a large scale, when extremely high speeds or great densities are involved, and for understanding gravity. On the other hand, the branch of physics known as quantum mechanics studies matter and energy at the smallest scales, including subatomic particles and processes. It has been difficult to fully join the two into one unified framework of physics. In an attempt to develop a unified theory, many physicists have turned to string theory. According to this theory, elementary particles are not dimensionless points but tiny one-dimensional stringlike objects. Although these “strings” are so small that they appear to be points, they actually have a tiny length. If 1 billion trillion trillion of them were laid end to end they would together be only about 0.4 inch (1 centimeter) long.

According to string theory, these strings make up all matter, and they vibrate. The particular pattern of a string’s vibrations corresponds to a particular type of particle. The strings that form electrons all have one vibrational pattern, for instance, while those that form quarks have a different pattern, and photons yet another.

In string theory, the universe is made up of more than the three dimensions of space and the one dimension of time that we observe. Instead, in most versions of the theory there are 11 dimensions (10 of space and one of time). The extra dimensions are curled up so as to be imperceptible.

String theory was first developed in the 1970s to describe the strong force. The theory became popular in the 1980s when it was shown that it might be a way to incorporate all types of matter and all four known forces, including gravity, into one framework. Such a comprehensive physical theory is known as a unified field theory or a “theory of everything.”

Although the mathematics of string theory has shown great promise, the theory has not yet been verified by experiment. Strings, if they exist, are extremely tiny. Physicists hope that the latest generation of particle accelerators will be able to detect such small objects. They are also seeking other ways to confirm string theory. In the meantime, it remains a totally theoretical construct.

Additional Reading

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(*See also* bibliographies for chemistry; energy; physics.)

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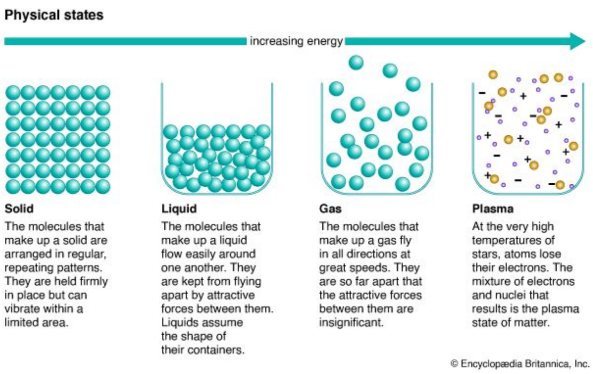
ARTICLE

gas

Gas is one of the three principle states of matter. The properties of gases are distinctly different from those of liquids and solids—the other principle states. Gases have neither a definite volume nor a definite shape. In contrast, both solids and liquids have a definite volume, and solids have a fixed shape. Liquids lack a shape of their own but take on the shape of the vessel that contains them. Gases will fill any closed container; however, this property depends on the volume of the container and not its shape.

Characteristics of Gases



The behavior of particles differs in each of the four states of matter.

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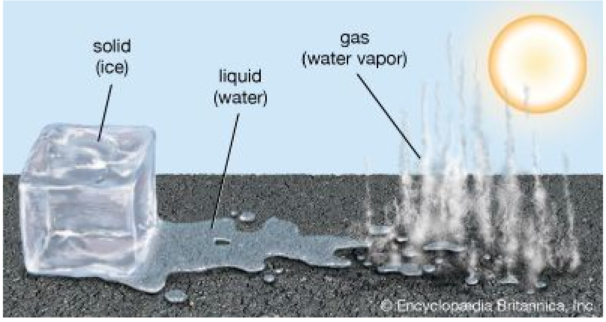
Like all matter, gases have mass, take up space, and are composed of particles (atoms and molecules) that move in relation to each other. Each state of matter is distinguished from the others by the behavior of its particles. The particles in a gas are farther apart compared to the particles in liquids and solids. The attractive forces that keep particles close together in the solid and the liquid states are very weak in the gas state. As a result, the particles in a gas can flow freely in every direction.

Although the particles in gases are very far apart, the amount of space between them can change. Like liquids, gases can flow because their particles are free to move about. Because the particles in a gas are free of attractive forces and can move easily in every direction, a gas will expand to fill its container. If the container is flexible, it will expand; this is observed when a balloon is inflated with gas. If the container is rigid and more gas is added, the volume of the gas will remain the same, but there will be less space between its particles than there was before. If some of the gas is released from the container, the remaining gas particles will again spread to fill the container. Even though there are fewer gas particles remaining in the container, the volume of the gas remains the same.

Changes of State

When a gas is cooled below a certain temperature, it can change state from the gaseous to the liquid state. This temperature is the boiling point of the substance. As the temperature of the gas approaches this point, the particles in the gas move at a slower speed. As the particles slow down, the attractive forces between them grow stronger, causing the particles to stay closer together. As the temperature moves below the boiling point, particles are moving slowly enough and are close enough to change phase from a gas to a liquid. The process through which a gas changes to a liquid is called condensation.

The process through which a liquid changes to a gas is called evaporation. In this process, as the temperature of a liquid approaches its boiling point, its particles begin to move faster and farther apart from each other. When the particles are moving fast enough to break free of the attractive forces keeping them together, the liquid begins to evaporate and change phase to the gas state.



The three principle states of matter are solid, liquid, and gas. Water exists in these states—as ice (solid), liquid water, and water vapor (gas). Like all gases, water vapor is invisible; it is shown here merely for the purpose of illustration.

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A familiar example of evaporation is what is observed when water boils. As a pot of liquid water is heated, the particles in the water move faster. When the temperature of the water approaches its boiling point (212 °F, or 100 °C), the particles near the surface of the liquid begin to “escape” from the liquid, changing into particles of water vapor that float into the air of the room. As these particles begin to cool, they condense on surfaces in the room as liquid water droplets.

An example of sublimation is the conversion of solid carbon dioxide (dry ice) to carbon dioxide gas.

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In general, solids change state first to a liquid and then to a gas. Under certain conditions, some solids can change state directly to a gas. This process is called sublimation. An example of such a solid is dry ice, which is actually frozen carbon dioxide and sublimates to form gaseous carbon dioxide at −109.3 °F (−78.5 °C). This temperature may be considered the “boiling point” of carbon dioxide because it marks the point at which carbon dioxide gas forms. However, because the process involved is actually sublimation, it is more properly called the sublimation point.

Condensation, evaporation, and sublimation are physical changes—changes in which the substance changes form but not composition. Thus mass is conserved when a gas changes to a liquid or a solid (and vice versa)—the same numbers and types of particles that comprise the gaseous state are found in the liquid and the solid phases.

Citation (MLA style):

"Gas." *Britannica LaunchPacks: The States of Matter*, Encyclopædia Britannica, 24 Jul. 2024. packs.eb.com. Accessed 4 May. 2025.

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ARTICLE

liquid

Liquid is one of the three principle states of matter. In its characteristics, a liquid is intermediate between a gas and a solid, the other two principle states. Like gases, liquids can flow and take on the shape of the container in which they are placed—characteristics not found in solids. Like solids, liquids have a fixed volume, whereas gases do not.

Liquid is one of the three principle states of matter. A liquid has a definite volume but not a definite shape. Instead, liquids take on the shape of the vessel they are in. The particles in a liquid are close together but can move about independently. As a result, liquids can flow from one vessel to another.

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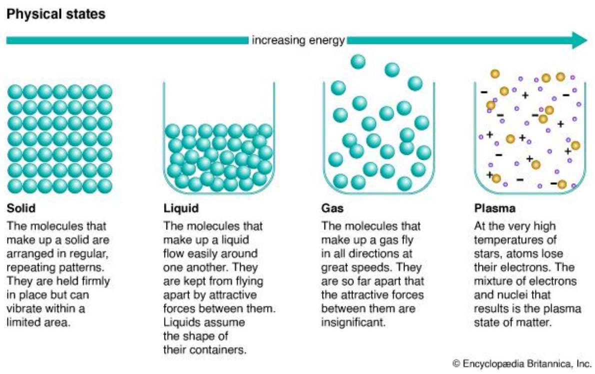
As with all forms of matter, a liquid is composed of particles—atoms and molecules—that move about in relation to each other. Each state is distinguished from the others by the behavior of its particles. The particles in a liquid are situated near each other but are not as close together as the particles in solids—nor as far apart as those in gases. Unlike the particles in solids, which are fixed in place, the particles in liquids can slide past each other, though they cannot move as freely as the particles in gases.



The behavior of particles differs in each of the four states of matter.

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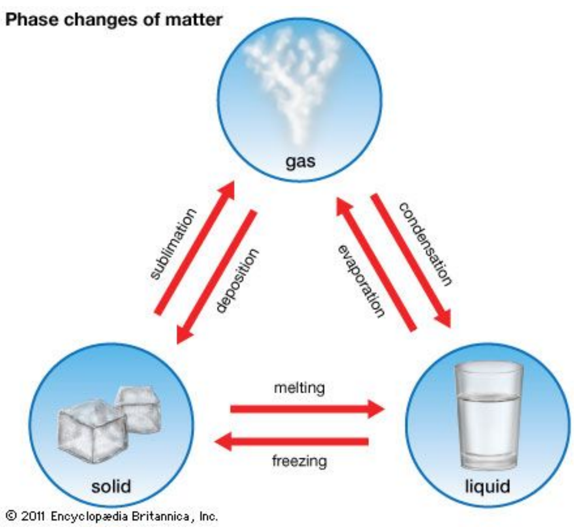
The behavior of the particles in each state of matter depends on the strength of the attractive forces between them. The attractive forces between particles in a liquid are weak enough to let the particles move around each other but strong enough to keep them from flying apart.

Characteristics of Liquids

Liquids have a definite volume but not a definite shape. The volume of a liquid can be measured and generally is expressed in units of liters. The shape of a liquid changes depending on the vessel containing it. If a given volume of a liquid is poured into a tall narrow container, the liquid takes on a tall narrow shape. If that liquid is transferred to a rounded bowl, it retains the same volume but takes on a rounded shape. These properties help to distinguish the liquid state from the solid and gaseous states of matter. Gases expand to fill their container so that the volume they occupy is the same as that of the container. Solids retain both their shape and volume when moved from one container to another.

Liquids may be divided into two general categories: pure liquids and liquid mixtures. On Earth, water is the most abundant liquid. Much of the water that organisms encounter is not in pure form, however. Instead, it is a mixture in which various substances are dissolved. For example, seawater is a liquid mixture in which a variety of salts are dissolved in water.

Boiling Point and Freezing Point



The phase changes of matter include melting, freezing, evaporation, condensation, deposition, and sublimation.

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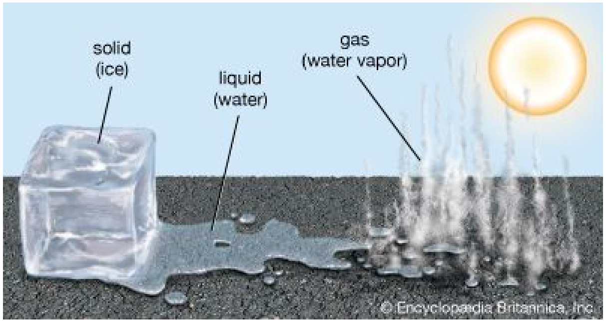
Like all matter, liquids can change state, moving from liquid to gas or from liquid to solid. A change of state can result when particle motion is altered because of changes in temperature.

Changes of state are physical changes; although a substance changes form, its composition does not change when it transitions from one state to another. Mass is thus conserved when liquid changes state to a gas or a solid: the same number and types of atoms in the liquid phase are found in the gas phase and the solid phase. (*See also*matter.)

When a liquid is heated, its particles begin to move faster. At a certain temperature, the particles are moving so quickly that they begin to escape the liquid phase and move freely as gas particles. The temperature at which a substance changes state from a liquid to a gas is called its boiling point. When a liquid is cooled, the reverse happens: as the temperature of a liquid decreases, its particles move more slowly. Below a certain temperature, the particles are close enough to form a solid. The temperature at which a substance changes from a liquid to a solid is called its freezing point. (The freezing point of a substance is the same temperature as its melting point—the temperature at which the solid form changes to a liquid.)



The three principle states of matter are solid, liquid, and gas. Water exists in these states—as ice (solid), liquid water, and water vapor (gas). Like all gases, water vapor is invisible; it is shown here merely for the purpose of illustration.

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Different substances have different freezing and boiling points. Water and acetic acid are both liquid at room temperature. However, water boils at 212 °F (100 °C) and freezes at 32 °F (0 °C); acetic acid, a component of vinegar, boils at 244.2 °F (117.9 °C) and freezes below 61.9 °F (16.6 °C). Most metals are solids at room temperature; the sole exception is mercury, which is liquid at room temperature. Mercury changes from a liquid to a solid when cooled below its freezing point of −37.97 °F (−38.87 °C); when heated above its boiling point of 674 °F (356.9 °C), mercury vaporizes to become a gas.

Citation (MLA style):

"Liquid." *Britannica LaunchPacks: The States of Matter*, Encyclopædia Britannica, 24 Jul. 2024. packs.eb.com. Accessed 4 May. 2025.

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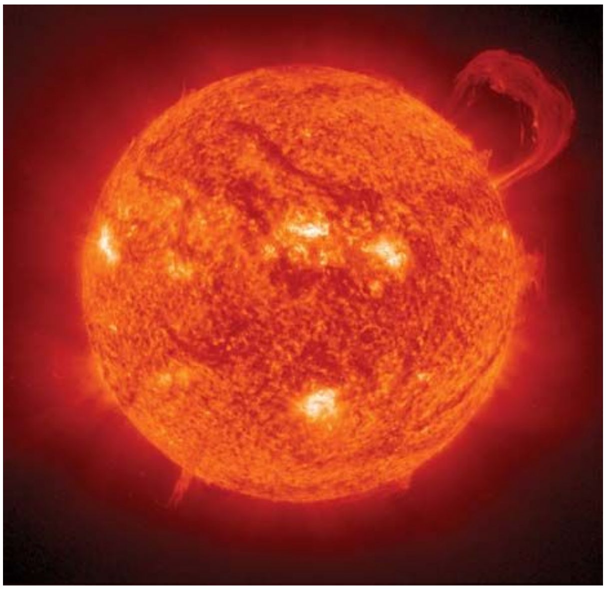
ARTICLE

plasma and plasma physics

When a gas is heated by many thousands of degrees, the individual atoms collide with enough violence to knock electrons free, resulting in a collection of positively charged ions and free, negatively charged electrons. The gas is said to be ionized, and when a sizable number of the atoms become ionized, the gas is called a plasma.



The interaction of the Sun's magnetic field with the motions of the plasma in and around the Sun causes spectacular phenomena such as this huge handle-shaped solar flare prominence.

NASA

A plasma can also be formed by applying other forms of energy to a gas: irradiating it with ultraviolet or X-rays, for example, or bombarding it with high-speed electrons, ions, or other particles. Because the free electrons tend to recombine with the ions to once again form a neutral gas, however, a plasma can be maintained only if the energy is continuously applied.

Scientists have estimated that more than 99 percent of the matter in the universe exists in the plasma state. Plasma exists in and around the stars, including the Sun, and throughout interstellar space.

Properties

Plasma is sometimes called the fourth state of matter because plasmas possess remarkable properties not found in ordinary solids, liquids, and gases. Because the free electrons are extremely mobile, for example, plasmas are excellent conductors of heat and electricity.

Plasma is unique in the way in which it interacts with itself and with electric and magnetic fields. The motions of the free electrons set up electric currents in the plasma. A magnetic field is usually associated with the plasma and interacts with these electric currents. On a small scale the magnetic field causes the individual ions and electrons to move in circles around the magnetic field. If the plasma is very hot, the circular motion of the electrons may cause them to emit radio waves. A local disturbance of the plasma causes complicated oscillations that propagate as waves through the plasma.

On a large scale the magnetic field moves with the plasma and is said to be “frozen in.” The pressure of the field and the tension along the magnetic lines of force act on the plasma, causing it to move in complicated ways.

Conversely, the turbulent motions of the plasma may churn the field, thereby stretching, tangling, and wrapping the field back on itself and reducing it to thinner and thinner ribbons of magnetic flux. This action continues until the individual ribbons are dissipated, or until the field becomes strong enough to resist the motions, creating a complicated dynamic balance between the field and the plasma.

Around a rotating star or galaxy, the plasma’s convective motion systematically folds the magnetic field into loops, producing the magnetic fields observed around these bodies. The interaction of the Sun’s magnetic field with the motions of the plasma in and around the Sun causes such spectacular phenomena as sunspots, prominences, and flares.

Plasma Physics

Plasmas are produced in the laboratory by applying a high voltage (100 to 100,000 volts) across a tenuous gas contained within a rigid metal or ceramic vacuum chamber. In most instances electric currents flowing through coils that surround the vacuum chamber are used to produce a strong magnetic field. The temperature of the gas may reach 1,800,000° F (1,000,000° C) or more once the gas is fully ionized. This method of heating may be supplemented by bombarding the gas with ions, electrons, and sometimes microwaves.

Once the plasma is created, the strong electric current flowing through it produces its own magnetic field, which circles the plasma column. In a phenomenon known as the pinch effect, the tension in the circling lines of force compresses the plasma column. In addition, the pressure of the field causes the column to buckle, resulting in so-called sausage and kink instabilities. To counteract these effects, the magnetic field of the external current coil is used to help stabilize and confine the plasma column.

With the proper magnetic-field configuration, plasma physicists had hoped to confine the plasma within the field, away from the cold walls of the chamber, so that the temperature of the plasma might be raised to temperatures high enough to initiate nuclear fusion. If this were achieved, scientists believe that plasma might one day provide a major share of the world’s nuclear power. In practice this goal has proved elusive, however, because of the remarkable ability of the plasma to squirm out of the confining magnetic field. Despite a variety of innovative approaches, including exotic magnetic-field configurations and faster methods of creating and heating the plasma, the problem remains unsolved. (*See also*physics.)

Eugene N. Parker

Citation (MLA style):

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ARTICLE

solid

On freezing winter days, a pail of water left outdoors soon changes in the way it looks and feels. Its chemical structure—H_2O—remains the same, but its physical state is different. It has frozen and turned to ice. It has changed from a liquid to a solid.

Ice keeps its own shape and size, but when it melts into water it loses its shape.

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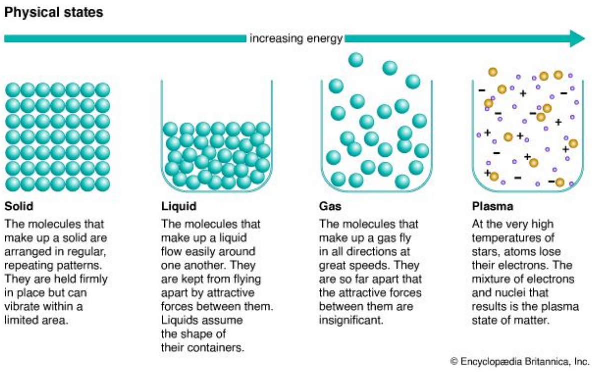
A solid is a state of matter that maintains its own shape instead of conforming to the shape of its container. If a piece of ice is placed in a cup, it does not flow downward and take on the shape of the cup, as liquid water would do. Instead, the ice keeps its own size and shape. However, water poured into a cup takes on the shape of the cup while it is in the cup.

At room temperature, steel, copper, and diamonds are solids. Individual grains of table salt are also solids at room temperature; each keeps its own shape and size. The state of a substance—that is, whether it is a solid, liquid, or gas—depends on its melting and freezing points.

Melting Points and Freezing Points

If the pail of ice is taken into a warm kitchen, it gradually grows warmer until it reaches a temperature of 32 °F (0 °C). It remains at that temperature during the time that it changes to its liquid form, a process called melting. Then its temperature rises until it equals that of the kitchen. If the pail of water is taken outdoors again, it cools back to 32 °F and remains at that temperature until it has changed back to the solid state, a process called freezing. Then its temperature sinks to the outdoor level. Both melting and freezing occur at the same temperature, in this case 32 °F (0 °C). This holds true for all substances that are crystals in their solid form.

The temperatures at which melting and freezing take place vary widely for different materials. Oxygen, for example, freezes at a very low temperature— –360 °F (–218 °C). Mercury, the only metal that is a liquid at normal room temperature, freezes at –38 °F (–39 °C). The freezing point for table salt is 1,474 °F, or 801 °C. This is far higher than the highest temperatures that normally occur on the Earth’s surface but low compared to the freezing points of many other solids. Iron, for example, has a freezing point of 2,795 °F (1,535 °C), and the freezing point of quartz is 2,930 °F (1,610 °C).



States of matter.

Encyclopædia Britannica, Inc.

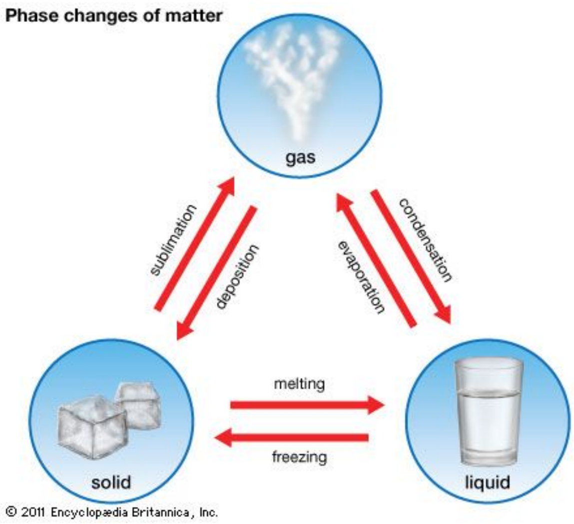
Scientists explain melting in terms of the energy of molecules and the attraction of molecules for one another. A molecule is the smallest unit of a substance that is still clearly that substance. Every molecule has energy of movement, whether it is traveling, rotating, or merely vibrating in place. Heat is the energy of the movement of molecules—the more quickly the molecules move, the hotter a substance is.

In solids, each molecule is held in place by the attractive forces of its neighbors, so it moves very little. But adding heat to a solid gives its molecules more energy of movement, so that they rotate and vibrate more strongly. The space each molecule takes up therefore increases, because it is moving about in a greater area. This causes the solid that comprises these molecules to expand.

The expansion of solids as they grow warmer has practical consequences. Engineers, for example, must make sure there are gaps in the metal of bridges so that there is room for the bridge to expand in warm weather. Otherwise, the structure would buckle or crack.

When the melting point for a substance has been reached, its molecules can gain too much energy to stay in one place. They break away from their fixed positions and move randomly. While the solid is melting, its temperature holds steady because all the heat applied to it goes to overcome the forces that hold the molecules in one place. Once the solid has melted completely, the heat applied to the substance again serves to speed up the movement of its molecules rather than to overcome the forces between them. The temperature of the substance therefore resumes its rise.

The stronger the attractive forces between the molecules of a solid, the higher its melting and boiling points will be. Very little energy is required to change oxygen from a solid to a liquid state because its molecules do not attract one another strongly. A great deal of energy, however, is required to change quartz from a solid to a liquid because the molecules of quartz are bound tightly together.



The phase changes of matter include melting, freezing, evaporation, condensation, deposition, and sublimation.

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Some solids do not melt and become liquids under normal conditions. Dry ice (solid carbon dioxide) is an example. At –110 °F (–79 °C) it changes from a solid to a gas. This process is called sublimation.

Kinds of Solids

Solids can be divided into two broad classes—crystals and amorphous solids. The molecules of both crystals and amorphous solids move within a circumscribed area. The molecules of crystals are arranged in regular symmetrical patterns. In contrast, the molecules of amorphous solids are located randomly, like those of liquids. Amorphous solids do not have a definite melting point but simply become more fluid as they are heated. For this reason, many scientists regard them as slow-flowing liquids.

A windowpane is a typical amorphous solid. Its basic structure consists of long chains of silicon dioxide that are linked together randomly to form a tangle of rings. Each of these rings contains a random number of silicon dioxide units. Quartz, a crystalline solid, also consists of rings of silicon dioxide. But they are arranged in a regular pattern.

Many plastics maintain their own shapes rather than flow to assume the shapes of their containers. Plastics are made of long chains of molecules. Some are partially crystallized when in the solid state: parts of the molecules line up in a regular order while the rest are randomly arranged. When such substances liquefy, the crystalline areas disappear and the whole material may become random.

Sometimes a solid is part of a composite structure that can include matter in several states. Biological solids, such as wood and bone, are composite materials. Wood contains lignin and cellulose, which are polymers, and living cells, which include liquids and dissolved solids. Lignin, a stiff cement, supports the strong and flexible cellulose molecules. Bone contains collagen, a strong, flexible polymer, and apatite, a hard and brittle calcium compound. Cells and food canals are scattered throughout this structure.

Uses of Solids

Solids can be hard (cement, for example) or soft (gold); brittle (eggshells), malleable (copper), or elastic (rubber); heavy (lead) or light (balsa wood). Some solids are good conductors of heat and electricity; others are insulators.

Solid state physicists and chemists study the relationship between the structure of solids and their physical properties. Their discoveries have led to the invention of such devices as lasers, transistors, and solar batteries.

Crystallographers study the arrangement of molecules in crystals. Metallurgists study metals and alloys.

Citation (MLA style):

"Solid." *Britannica LaunchPacks: The States of Matter*, Encyclopædia Britannica, 24 Jul. 2024. packs.eb.com. Accessed 4 May. 2025.

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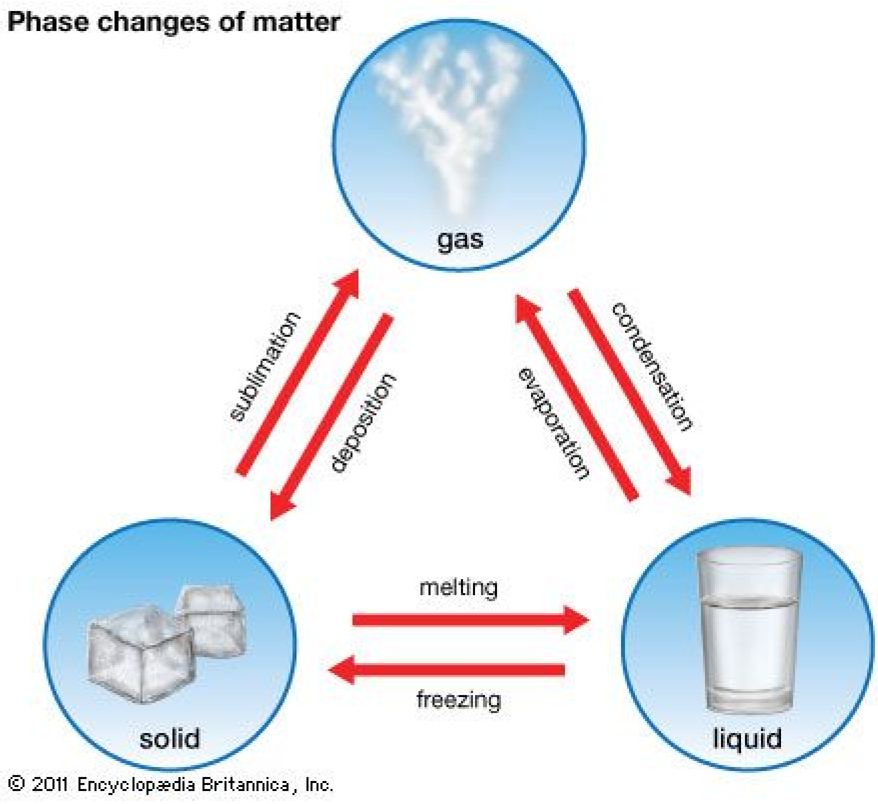
IMAGE

matter: phase changes



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Matter: phase changes. Image. *Britannica LaunchPacks: The States of Matter*, Encyclopædia Britannica, 23 Mar. 2025. packs.eb.com. Accessed 4 May. 2025.

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VIDEO

How states of matter transform: Solid, liquid, and gas

Video Transcript

Matter exists in several different forms, called states. The three most familiar states are solid, liquid, and gas. All matter is made up of tiny particles called molecules. The molecules that make up a solid are arranged in regular, repeating patterns. [PR1]Attractive forces between the molecules hold them firmly in place. However, the molecules can vibrate, or move slightly. The molecules that make up a liquid flow easily around one another. Attractive forces between the molecules keep them from flying apart. Liquids take on the shape of their containers. The molecules that make up a gas fly in all directions at great speeds. Attractive forces between the molecules are not strong enough to hold them together. Increased energy, such as heat, can cause matter to change from one state to another as the increased energy makes the molecules in the matter move faster. For example, when water in the solid form of ice is heated, its molecules move faster and farther apart. Eventually the ice will melt into liquid water. When liquid water is heated to a high enough temperature, its molecules move fast enough to break loose and fly into the air to form a vapor, or gas. Cooling temperatures reverse the process.

The three most familiar forms, or states, of matter are solid, liquid, and gas. Heating and cooling a substance may change it from one state to another.

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Citation (MLA style):

How states of matter transform: Solid, liquid, and gas. Video. *Britannica LaunchPacks: The States of Matter*, Encyclopædia Britannica, 23 Mar. 2025. packs.eb.com. Accessed 4 May. 2025.

VIDEO

glass

Video Transcript

Many church windows are small works of art, and as ancient as the walls that surround them. A legend surrounding them is also very old. Church windows are said to be thicker at the bottom than they are at the top. It is claimed that the glass has slowly seeped to the bottom, like a very thick liquid. Does cold glass really behave like sticky honey? In liquids, molecules move about with great freedom. This is why they are able to flow. Glass, too, is made up of molecules. However, these molecules are not free to move, they are frozen solid and there is no movement whatsoever. Glass has almost exactly the same properties as crystal, which is also made up of molecules. The difference between crystal and glass is that crystals have a regular periodic structure. From a physical perspective this means that glass cannot flow, that is it cannot be thicker at the bottom. So does that mean the legend surrounding glass is utterly bogus? Perhaps we'll find the answer at the Glashütte Lamberts glass factory on the German-Czech border. Here they make panes of glass as people did in the Middle Ages. The gob of molten glass is blown into a bulb, and then the glassblower forms it into a long cylindrical shape. It doesn't yet look like a windowpane, but the glassblowers aren't quite finished. The glassblowers take a critical step forward creating a pane of glass using a trick. The glass cylinder with its ends removed is put in the oven one more time so it can be shaped again. A simple block of wood is used to flatten the glass into a pane. But we wanted to know one more thing. How thick is the pane of glass? To answer this question they perform a test especially for us. The glassmaker shows us if the pane of glass is of the same thickness everywhere on its surface. And here is the result: 2.51 millimeters at one end and 3.04 millimeters at the other. This means that if an old pane of glass varies in thickness, it was always like that from the very beginning.

Some old window panes are thicker at the bottom. Does this mean that glass is a liquid with an extremely slow rate of flow? Journalists find another explanation.

Contunico © ZDF Studios GmbH, Mainz; Thumbnail © Chun Ju Wu/Dreamstime.com

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Citation (MLA style):

Glass. Video. *Britannica LaunchPacks: The States of Matter*, Encyclopædia Britannica, 23 Mar. 2025. packs.eb.com. Accessed 4 May. 2025.

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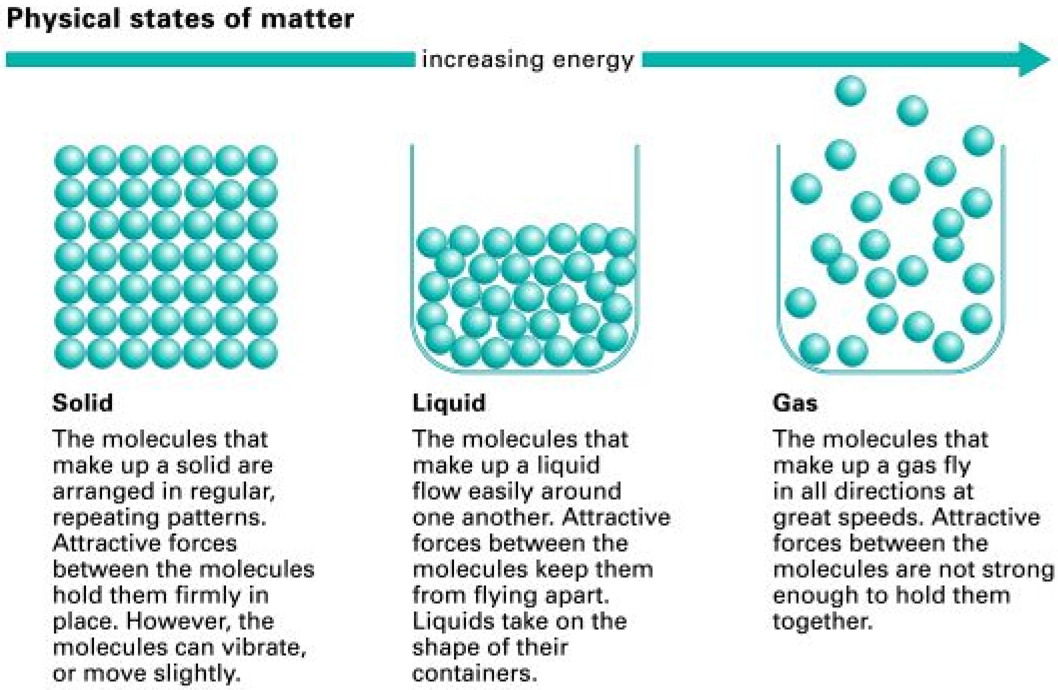
INTERACTIVE

matter: states of matter

Britannica Note:

This is an interactive illustration of solids, liquids, and gases.



All materials are made up of matter. Matter is anything that takes up space. The three most familiar forms, or states, of matter are solid, liquid, and gas. Heating and cooling a substance may change it from one state to another. When a material changes state, its smallest units, called molecules, behave differently. However, the material's molecules do not break apart and form into a different material. They remain the same. A change of state is a reversible change.

Encyclopædia Britannica, Inc./Kenny Chmielewski

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