9

Atomic Structure and Phases of Matter

KEY IDEA

All matter consists of atoms, the building blocks of our world.

PHYSICS AROUND US . . . Solid to Liquid to Gas

You are walking along the street on a hot summer day, sipping an iced drink. Jostled by a passerby, you inadvertently spill some of the drink and an ice cube falls onto the sidewalk. In a few moments, the hard piece of ice begins to melt and is surrounded by a small puddle. Eventually, the ice cube disappears entirely, becoming a flat pool of water. One-half hour later, the water itself is gone, evaporated into the air.

A steelworker manipulates the controls of his console, tipping a huge bucket of red-hot molten steel into a mold. As the steel cools and solidifies, it is rolled into a sheet of tough, solid metal—perhaps a sheet that will be used to form the body of your next car.

You place a pot of water on the stove to boil water for coffee. A phone call distracts you and you forget all about it. Disaster is averted only when your roommate warns you that the water has all boiled off and the pot is about to burn.

All around us matter changes its physical form, from solids to liquids to gases and back again. The easiest way to understand these remarkable transformations is to realize that matter is made of invisibly small bits of material called *atoms*.

ENERGY, ATOMS, AND THERMODYNAMICS

In Chapter 8 we discuss the importance of the concept of energy in all areas of science, as well as in our daily lives. We take for granted the availability of energy in today's world. We just flick a switch or press a button and lights appear, computers start up, and we hear our favorite songs or see our favorite movies. Finding and securing energy resources has been one of the driving forces of global politics and economics for the past century or more and is still a vital concern for all nations. The by-products of energy consumption and their effects on the world environment have become a major concern as well.

It wasn't always like this. The ideas that energy could be measured and that changes in energy followed certain laws developed gradually during the late eighteenth and nineteenth centuries. The study of energy is known as **thermodynamics** and various physicists contributed to the laws of thermodynamics by the time the twentieth century dawned. However, there was no overall understanding as to why these laws worked. For instance, according to the first and second laws of thermodynamics, you can never build a perpetual motion machine, which would produce more energy than you put into it to make it run. Why not? Many physicists of the time would probably have answered, "Because the law says so, that's why not."

The great change in understanding the laws of energy came about from another fundamental idea in physics: that all matter consists of tiny particles called **atoms.** This idea has actually been around since the time of the ancient Greeks, over 2000 years ago. However, only in relatively recent times has it become clear that the behavior of matter at the atomic level actually determines what we observe and measure all around us. And one of the basic factors that most affects the behavior of atoms is energy.

The laws of thermodynamics deal with energy in the forms of heat, thermal energy, and work. However, before we discuss these ideas, in this chapter we introduce the atomic structure of matter and show how the energy of atoms affects whether a substance is solid, liquid, or gas. We show in later chapters that the atomic theory explains other properties of matter, from thermal expansion to strength of materials. With that discussion as background, we can explore what happens to a system of objects when the energy of the system changes.

ATOMS: THE BUILDING BLOCKS OF MATTER

In the first eight chapters we have examined everyday physical behavior of objects, including forces, which can cause objects to change their motion, and energy, which is necessary to exert a force over a distance. But what of physical objects themselves? What is the nature of matter, and why do objects display such an astonishing range of properties? To answer these questions we need to look at matter in much finer detail.

Imagine that you took a page from this book and cut it in half, then cut the half in half, cut half of that in half, and so on. Only two outcomes to this process are possible. If paper is smooth and continuous, there would be no end to this process, no smallest piece of paper that couldn't be cut further. On the other hand, you might come to a piece that could be divided no further, a smallest piece of matter. In which world do we live, a world where matter is continuous or a world in which there is a smallest piece? Finding the answer to this question has occupied many great minds over the course of more than 2500 years.

The Greek Atom

About 530 B.C. a group of Greek philosophers, the most famous of whom was a man named Democritus, gave this question some serious thought. Democritus argued (purely on philosophical grounds) that if you took the world's sharpest knife and started slicing chunks of matter, you would eventually come to a smallest piece—a piece that could not be divided further (Figure 9-1). He called this smallest piece the *atom,* which translates roughly as "that which cannot be cut." He argued that all material was formed from these atoms and that the atoms are eternal and unchanging, but that the relationships among atoms are constantly shifting. This argument provided a kind of intellectual bridge between two schools of thought among Greek philosophers, one of which argued that the fundamental reality of the world had to be eternal and unchanging, and the other that change was omnipresent in the universe.

It is important to realize that the Greek atomic theory is a part of philosophy and not part of science. For example, there is no place in it for observations and experiments. The only part of this historical episode that survives in modern science is the word *atom* itself, although even here, as we shall see in Chapter 21, it doesn't really describe the modern atom.

Elements

The beginning of modern atomic theory is generally attributed to an English meteorologist, John Dalton (1766–1844). In 1808, Dalton published a book titled *New System of Chemical Philosophy,* in which he argued that the new knowledge being gained by chemists about materials provided evidence, in and of itself, that matter was composed of atoms. Chemists knew that most materials can be broken down into simpler chemicals. If you burn wood, for example, you get carbon

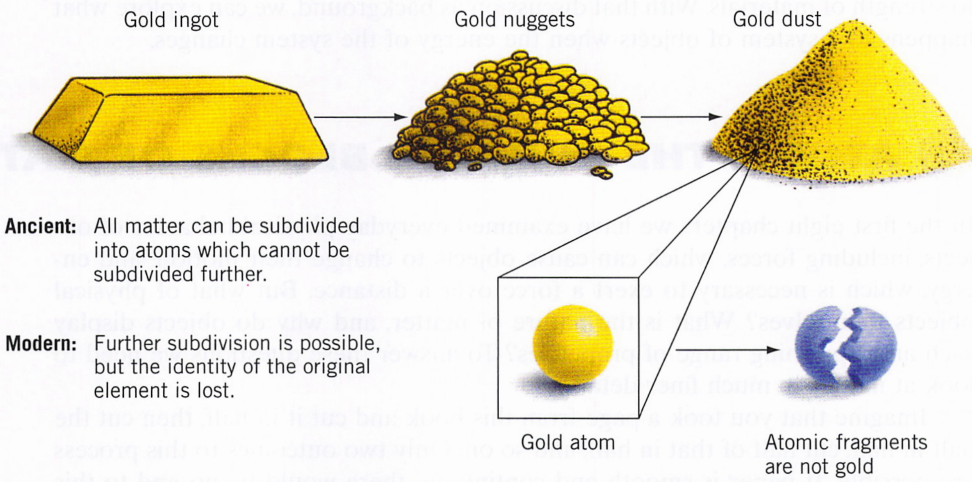
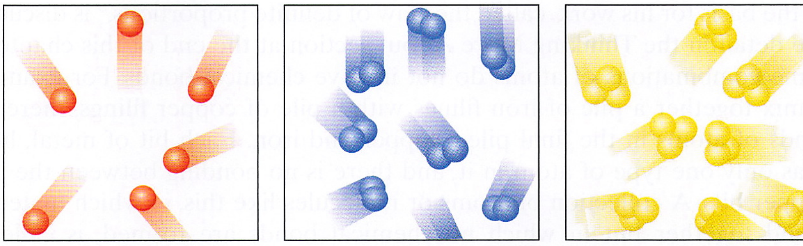


FIGURE 9-1. Repeatedly dividing a bar of gold, just like cutting paper repeatedly, produces smaller and smaller groups of atoms, until you come to a single gold atom. That single atom cannot be divided further by chemical means.



(*a*) Atoms (*b*) Diatomic (two-atom) molecules (*c*) Triatomic (three-atom) molecules

FIGURE 9-2. Atoms may be envisioned as solid balls that stick together to form molecules. Atomic models are often drawn with spheres, although we know that atoms are not solid objects. With this model, we can think of atoms as single spheres (*a*) and molecules as double spheres (*b*), triple spheres (*c*), or more.

dioxide, water, and all sorts of materials in the ash. If you use an electric current to break down water, you get the two gases hydrogen and oxygen. Dalton and his contemporaries also recognized that a few materials, called **elements,** could not be broken down into other substances. For example, you can heat wood to get charcoal (essentially pure carbon), but try as you might, you can't break down the carbon any further. Thus, chemists recognized that carbon is an element.

The hypothesis that we now call "atomism" was very simple. Dalton suggested that each chemical element corresponded to a species of indivisible objects called **atoms.** He borrowed this name from the Greeks, but other aspects of Dalton's theory were quite new. Two or more atoms stuck together form a **molecule**—the same term applies to any cluster of atoms that can be isolated, whether it contains two atoms or 1000. Molecules make up many of the different kinds of material we see around us. For example, a water molecule comprises one oxygen atom and two hydrogen atoms (thus, the familiar formula H_2O). In Dalton's view, atoms were truly indivisible—he thought of them as little bowling balls (Figure 9-2). In Dalton's world, then, indivisible atoms provide the fundamental building blocks of all matter.

ATOMS IN COMBINATION: COMPOUNDS AND MIXTURES

John Dalton saw chemical reactions, such as wood burning or a piece of metal dissolving in acid, as processes that involved the putting together and taking apart of various combinations of atoms. In fact, if you think of Dalton's atom as something like a bowling ball with Velcro patches scattered around its surface, you wouldn't be far off. Just as two bowling balls can stick together if their Velcro patches align, so too can two atoms come together to create a molecule. And just as you can separate the bowling balls if you apply enough force, so too can a molecule be broken down into its individual atoms. Today, as we see in Chapter 23, we refer to the matched "Velcro patches" that tie atoms together as *chemical bonds.* Materials such as water, consisting of molecules in which atoms are held together by chemical bonds, are called **compounds.**

Unlike the Greek philosophers, Dalton based his theory of the atom on a large amount of data from chemical experiments. One important law that was

Sand is a mixture composed of different kinds of light and dark grains. The white line gives the scale of 1 mm.

part of the basis for his work, called the "law of definite proportions," is discussed in more detail in the Thinking More About section at the end of this chapter.

Some combinations of atoms do not involve chemical bonds. For example, if you mix together a pile of iron filings with a pile of copper filings, there are two kinds of atoms in the final pile—copper and iron. Each bit of metal, however, has only one type of atom in it, and there is no bonding between the iron and copper bits. A collection of atoms or molecules like this, in which materials are found together but in which no chemical bonds are formed, is called a **mixture.** Sand on the beach is a common mixture, as are a cup of coffee with cream and sugar and even the air you breathe.

Physics in the Making

The Father of Modern Chemistry

One of the basic ideas on which Dalton's atomic theory rested was the principle of conservation of mass. This principle states that in a chemical reaction, there is no overall change in amount of mass—reactants may change their form and produce other substances, but mass is not destroyed. This is not an obvious concept; for example, if you burn a log in a campfire, producing smoke and ash, it certainly looks like mass has been lost. But if you trap all the smoke and weigh it along with the ash, you will find that the weight is the same as the initial log. The person who first proved this result, with experiments on combustion among other things, was Antoine Lavoisier (1743–1794).

Lavoisier was the first scientist to insist on the importance of quantitative measurements in chemical research. His textbook, *Traité Élémentaire de Chimie,* is the basis for modern chemical terminology and has been compared in its importance to chemistry with the influence of Newton's *Principia* in physics. Lavoisier disproved the accepted idea of combustion prevalent in the eighteenth century (the "phlogiston theory") and Dalton's work would not have been possible without Lavoisier's contributions.

Lavoisier was a member of the French nobility and the chief tax collector for an area of Paris. This made him a target of the French Revolution, and he was guillotined near the end of the Reign of Terror. ●

ATOMIC MASS

In Dalton's theory, all atoms of the same species are identical, but atoms of different species have different masses. Measuring these masses was accomplished in the nineteenth century using a chemical principle first enunciated in 1811 by the Italian scientist Amedeo Avogadro (1776–1856). **Avogadro's principle** states that equal volumes of any gas at the same temperature and pressure must contain the same number of molecules.

To see how this fact was used to determine the relative masses of atoms, consider a simple electrolysis experiment in which an electric current is used to break up water molecules (Figure 9-3). In such an experiment, the volume of hydrogen gas produced (due to the number of hydrogen atoms) is twice the volume of oxygen (due to the number of oxygen atoms). This ratio of hydrogen to oxygen is expressed by the familiar chemical formula H_2O. Thus, half the weight of the hydrogen gas released from water, compared to the weight of the oxygen gas

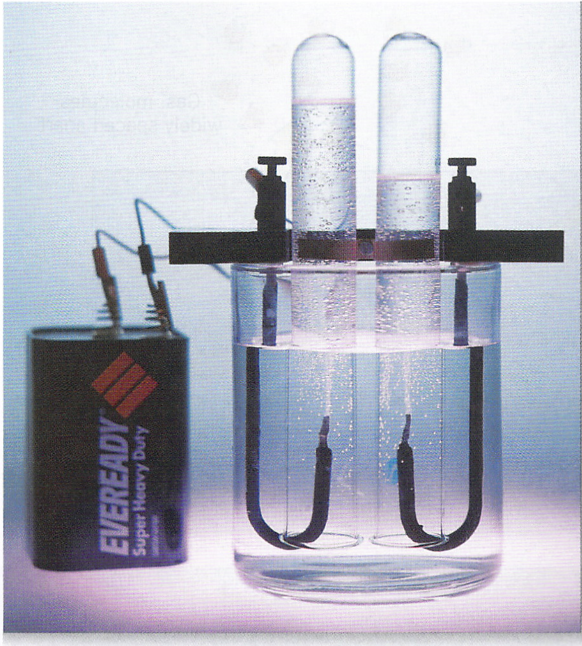


FIGURE 9-3. An electrolysis experiment on water shows that water separates into oxygen gas and hydrogen gas. The volume of the hydrogen is twice that of the oxygen, but the weight of the oxygen is eight times that of the hydrogen.

released, should yield the relative weights (and thus the relative masses) of the hydrogen and oxygen atoms.

In fact, when this experiment is done, the weight of the oxygen produced is about eight times the weight of the total amount of hydrogen, or 16 times the weight of half the hydrogen. If we define the mass of the hydrogen atom to be 1 atomic mass unit, then this result tells us that the oxygen atom has a mass 16 times that of hydrogen, or 16 atomic mass units.

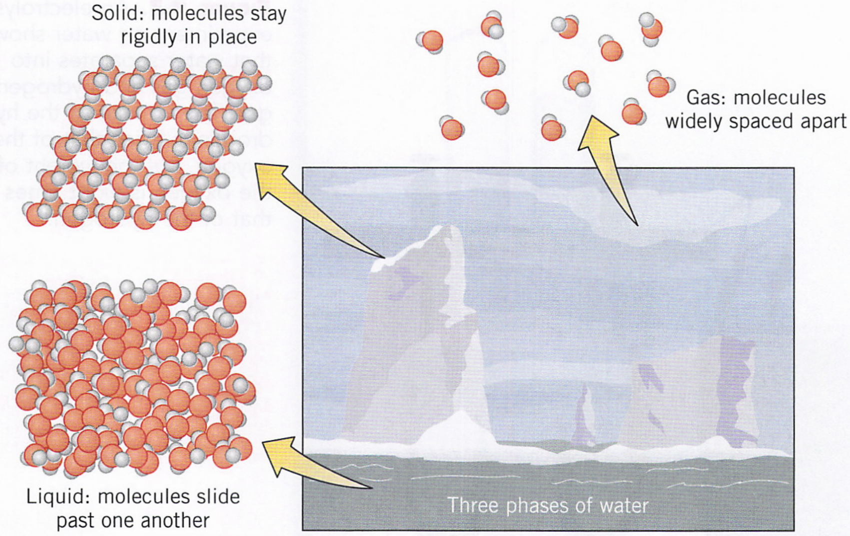
Using similar techniques, we can determine the other atomic masses relative to hydrogen. Thus, the atomic mass of carbon is about 12, iron is 56, silver is 108, and gold is 197. When we speak of the mass (or weight) of an atom, we are referring to masses measured in this way, relative to hydrogen with atomic mass 1. (For technical reasons, today the atomic mass unit is defined in terms of carbon, not hydrogen, but the mass of carbon is still 12 units and the mass of a hydrogen atom is still 1 unit.)

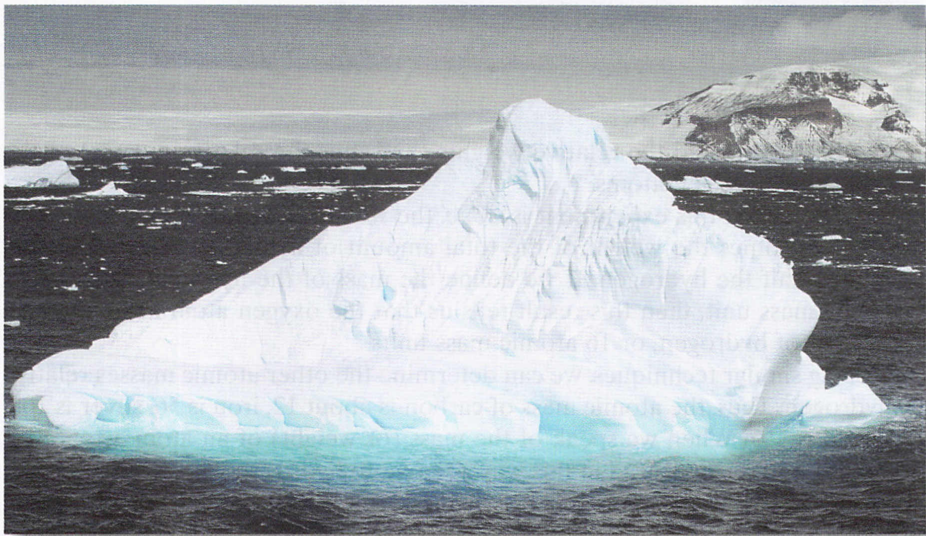
PHASES OF MATTER

Once we understand that all materials are made from atoms, we can explain the kinds of transformations discussed in the Physics Around Us section at the beginning of this chapter. A given material may be made from certain groups of atoms or molecules, but how those atoms or molecules are arranged can lead the material to have very different properties.

For example, water always consists of molecules containing two hydrogen atoms and one oxygen atom. Water can appear in its familiar liquid form, but it can also be solid ice or it can be gaseous steam. Whatever its form, however, it is still made up of the same molecules. What changes is the effectiveness of the forces that hold those molecules together, due to the different energies of the molecules in water, ice, or steam.

FIGURE 9-4. Water occurs commonly in three different states—solid, liquid, and gas. These three states of matter differ in the organization of their molecules.





The three forms that water can take are examples of **phases of matter.** The three most common phases of matter are solid, liquid, and gas (Figure 9-4).

The Solid Phase

A **solid** is defined as a material that has a definite shape and volume and that is sufficiently rigid to counteract a force imposed on it. For example, if you squeeze this book, it doesn't collapse but exerts a force to counter your squeezing. This counter-force is what you feel in your fingers.

In Figure 9-5 we show one way that atoms can be combined to form a solid. Atoms in many solids are arranged in a regular, repeating array and they are held together by interatomic forces called *chemical bonds.* We discuss the exact nature of these forces in Chapter 23, but for the moment the easiest way to think about chemical bonds is to imagine that the atoms are held together by stiff springs, as shown in Figure 9-5*c*.

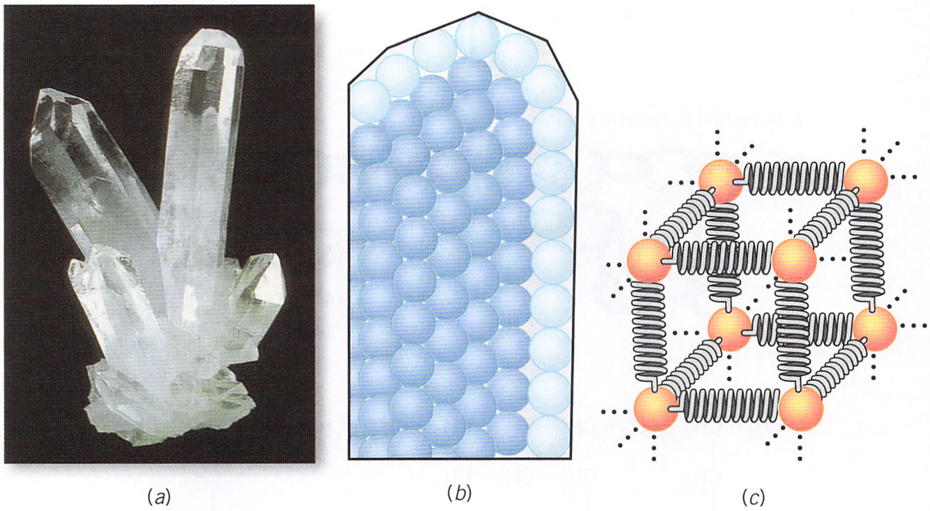


FIGURE 9-5. (*a*) A solid such as this quartz crystal has sharp, definite edges, reflecting the internal arrangement of its molecules. (*b*) A three-dimensional drawing of the crystal's regular arrangement of molecules. (*c*) Atoms are held together by bonds that behave like stiff springs.

A regular, repeating structure such as this is called a *crystal.* At the atomic level, solids from diamonds to table salt are arranged in this orderly way. You can think of a crystal as being formed from countless trillions of tiny boxes, each no more than a billionth of an inch on an edge, each in contact with several other identical boxes and containing exactly the same pattern of atoms (Figure 9-6). The key point is that atoms in a solid are locked into place and do not easily move around from one location to another. If you push on a crystal from the outside, the "springs" that hold the atoms together are compressed, and, by Newton's third law, exert a force that pushes back. This counter-force is how solids retain their shape when acted on by an outside force.

It is important to realize that crystals are only one way that atoms can arrange themselves into solids. In contrast to crystals, *glasses* include solids with predictable local atomic environments for most atoms, but no long-range order to the atomic structure (Figure 9-7). For example, in most common window and bottle glass, silicon and oxygen atoms form a strong three-dimensional framework with each silicon atom surrounded by four oxygen atoms. If you were placed on any atom in a glass, chances are you could predict the neighboring atoms. Nevertheless, glasses have no regularly stacked boxes of structure. Travel more than two or three atoms distant from any starting point and there is no way that you could predict whether you'd find a silicon atom or an oxygen atom.

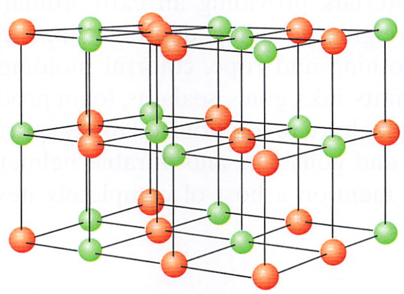


FIGURE 9-6. A crystal structure can be thought of as stacks of tiny boxes, each with the same pattern of atoms, arranged in a regular array.

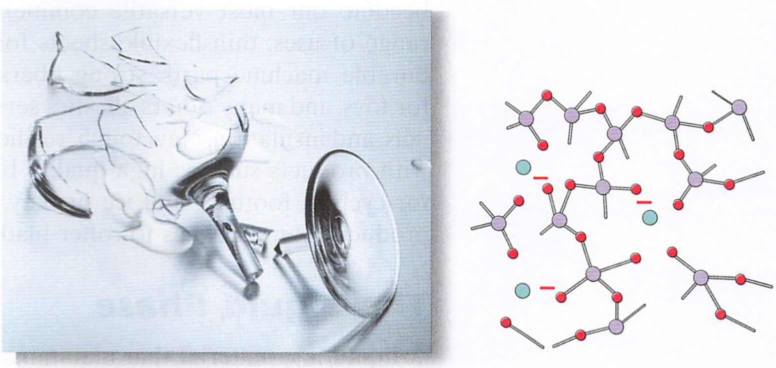
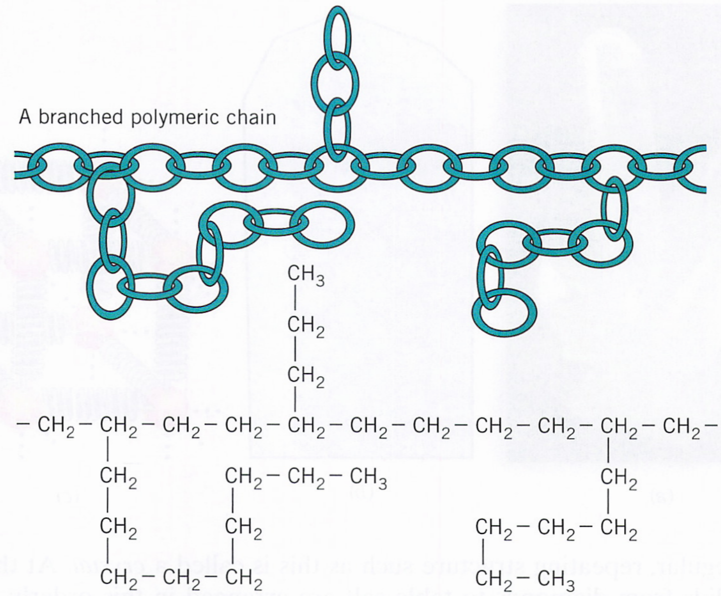
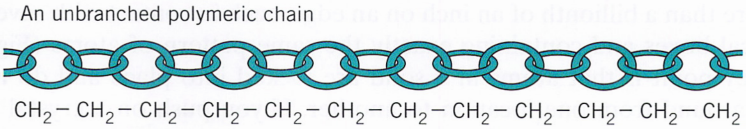


FIGURE 9-7. Glass is not arranged in a regular pattern of atoms; it does not form geometrical crystals.



(a)



(b)

FIGURE 9-8. (*a*) Branching and (*b*) unbranching polymers form from small molecules, just as long chains can form individual links.

Another kind of noncrystalline solid is a polymer. *Polymers* are extremely long and large molecules that are formed from numerous repeating smaller molecules like links of a chain. The atomic structure of these materials is often linear, with predictable repeating sequences of atoms along the polymer chain as well as branching side groups of atoms (Figure 9-8). Common polymers include numerous biological materials, such as animal hair, plant cellulose, cotton, spider webs, and clotted blood. Even DNA and RNA are polymers.

Polymers include all *plastics,* which are synthetic materials formed primarily from petroleum. A ubiquitous form of solid in our modern world, plastic features long chainlike molecules that are interlocked together like tangled strands of spaghetti in a bowl. Although almost unknown one-half century ago, plastics have become our most versatile commercial materials, providing an extraordinary range of uses: thin flexible sheets for lightweight packaging, dense castings for durable machine parts, strong fibers for clothing and rope, colorful moldings for toys, and many others. Plastics serve as paints, inks, glues, sealants, foam products, and insulation. New tough, resilient plastics have revolutionized many sports with products such as high-quality bowling and golf balls and durable helmets for cycling, football, and ice hockey, not to mention a host of completely new products from Frisbees to roller blades.

The Liquid Phase

A **liquid** is a material that maintains a constant volume, but assumes the shape of its container. Other than water, mercury, and a few biological fluids, few liquids occur naturally on Earth (at ordinary temperatures and pressures). Water, by far the most abundant liquid on the Earth's surface, is a dynamic component of geological change. In addition, water-based solutions are essential to all known forms of life.

In contrast to solids, atoms or molecules in a liquid do not stay in one place, but are free to slide over one another. You can picture the atoms or molecules in a liquid as being something like a container full of dry sand grains. The sand fills whatever volume it is poured into because individual sand grains can roll over one another. If the sand is poured into another container, the pile adjusts to conform to the new shape. By the same token, the relatively weak forces that hold the molecules together in a liquid suffice to keep the total volume of the liquid constant, but do not lock individual atoms in place. These forces are the same as those in a solid, but the molecules in a liquid have more energy and move around faster than molecules in a solid. As a result, the intermolecular forces are less effective at holding the molecules in place.

Connection

Surface Tension

Every molecule in a liquid has a weak attraction to every other molecule next to it. However, molecules at the surface of a liquid do not have any other molecules of the liquid above them, only below them. As a result, surface molecules experience a net force pulling them inward toward the rest of the liquid. This force is known as surface tension.

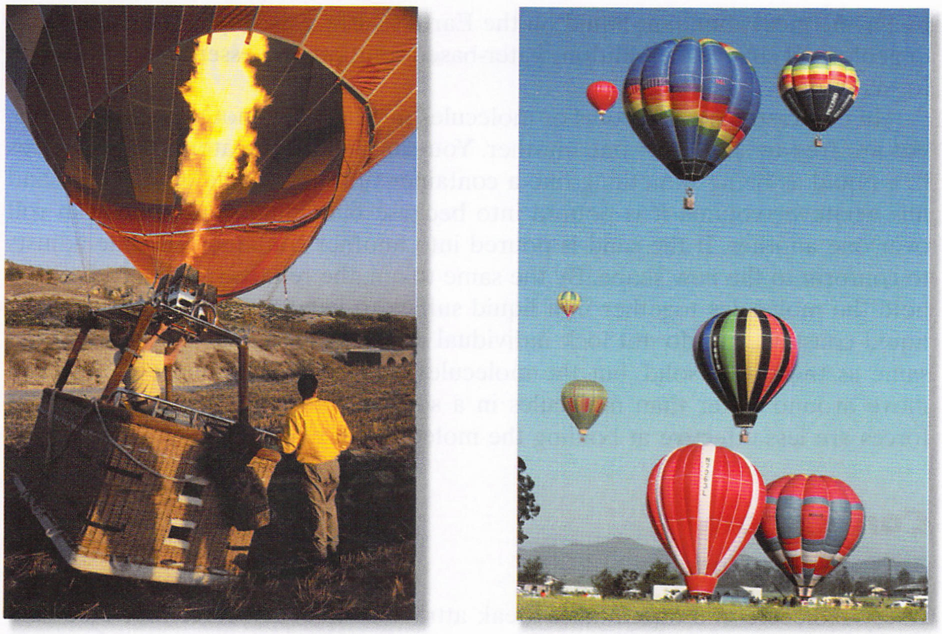
Surface tension in water is not a very large force, but it's enough to support the weight of light insects (e.g., water striders) or even a paper clip. Soap bubbles are round because the surface tension of the soapy water tries to minimize the area of the bubble around the volume of air inside; it turns out that a sphere has less surface area for a given volume than any other shape. In your lungs, the many tiny sacs (alveoli) where oxygen is absorbed by the bloodstream and carbon dioxide is released are also spherical. If these sacs had the same surface tension as water does, air pressure would not be enough to expand them. However, the alveoli are coated with a mucous lining that has a lower surface tension, enabling them to expand and fill up with air.

Surface tension is also the property of liquids that enables them to expand up into a thin tube, or capillary; the phenomenon is called "capillarity." You can see this behavior whenever you see water absorbed by the tiny spaces between fibers of a paper towel, but it is much more widespread than that. Capillarity has a role in the flow of blood through the smallest veins and arteries of the body (the capillaries) and is also involved in the transport of water and sap from the roots of trees to their upper branches. Can you see why surface tension is a topic of great importance in biology? ●

The Gaseous Phase

A **gas** is a material that retains neither its shape nor its volume, but expands to fill any empty container in which it is placed. The atoms or molecules in a gas are relatively far apart from one another and interact primarily by collisions. Thus, if gas is introduced into a container, the atoms rush outward until they encounter a wall, bounce off it, and return to collide with other atoms or molecules.

When a molecule of gas bounces off the walls of a container, Newton's first law of motion tells us that the wall must have exerted a force on the molecule. After



(*a*) (*b*)

(*a*) Hot air balloon being filled with gas. (*b*) The balloon rises because its average density is less than that of air.

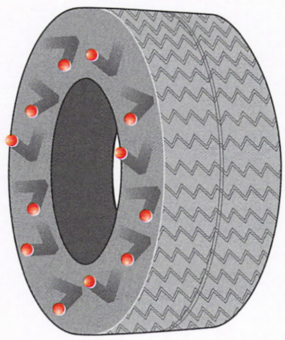


FIGURE 9-9. Gas molecules move constantly inside a tire. When they bounce off the inner walls of the tire, they cause an internal pressure.

all, that law tells us that, if an object with mass (such as a molecule) accelerates (by changing its direction of motion), then a force must have been applied to it. Newton's third law tells us that the molecule must also exert an equal and opposite force on the container. It is these collisions of countless molecules with the side of an automobile's tire, for example, that we perceive as air pressure (Figure 9-9).

The most common gas in our experience is the Earth's atmosphere, which is a mixture of oxygen and nitrogen, along with minor amounts of a few other gases (Figure 9-10). Even though you can't see the air around you, you can feel the effects of the gas molecules when the wind blows and exerts a force on you.

The term *fluid* is often used to refer collectively to both liquids and gases—materials that can change their shapes because individual atoms and molecules are free to change their positions.

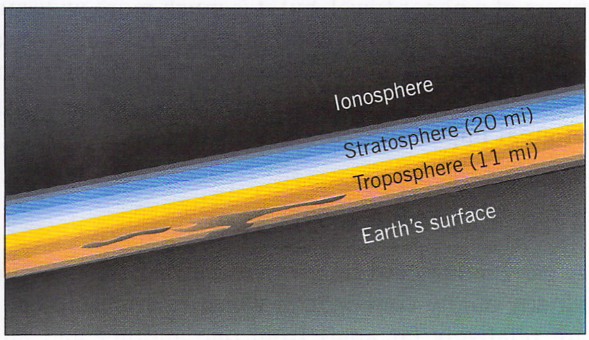


FIGURE 9-10. Earth's atmosphere is a thin shell surrounding the solid and liquid parts of the planet. The air we breathe is mostly in the troposphere; clouds generally mark the boundary between the troposphere and the higher stratosphere.

Connection

The Fourth Phase of Matter

At extreme temperatures such as those of the Sun, high-energy collisions between atoms may begin to break the atoms down into even smaller particles called "electrons" and "nuclei" (see Chapter 26). Extreme heat can strip off electrons, creating a *plasma,* in which positive nuclei move about in a sea of electrons. Such a collection of electrically charged atoms is something like a gas, but displays unusual properties not seen in other states of matter. For example, plasmas are efficient conductors of electricity. They are too hot and reactive to be confined in any normal container, but can be confined in a strong magnetic field, or "magnetic bottle."

A plasma is the least familiar phase of matter to us, yet more than 99.9% of all the visible mass in the universe exists in this form. Not only are most stars composed of a dense hydrogen- and helium-rich plasma mixture, but several planets, including the Earth, have regions of thin plasma in their outer atmospheres. ●

CHANGES OF PHASE

In all of the discussion so far of phases of matter, we have omitted one very important fact: atoms and molecules are constantly in motion, even in solids and liquids. As we see in Chapter 11, the hotter a material is, the faster those atoms or molecules move.

Take a crystalline solid as an example of this point. Atoms are locked into place by the "springs" we call chemical bonds, but each atom wiggles around its equilibrium position in the solid. On the atomic scale, think of the solid as being in a constant state of microscopic jiggling and shaking, like a bowl of Jell-O during an earthquake. As the solid heats up, this atomic jiggling gets more and more violent until, when it gets hot enough, the atoms simply tear loose from their moorings and start to move around over each other. At this point, the material changes from a solid to a liquid (Figure 9-11). We say that the material has melted.

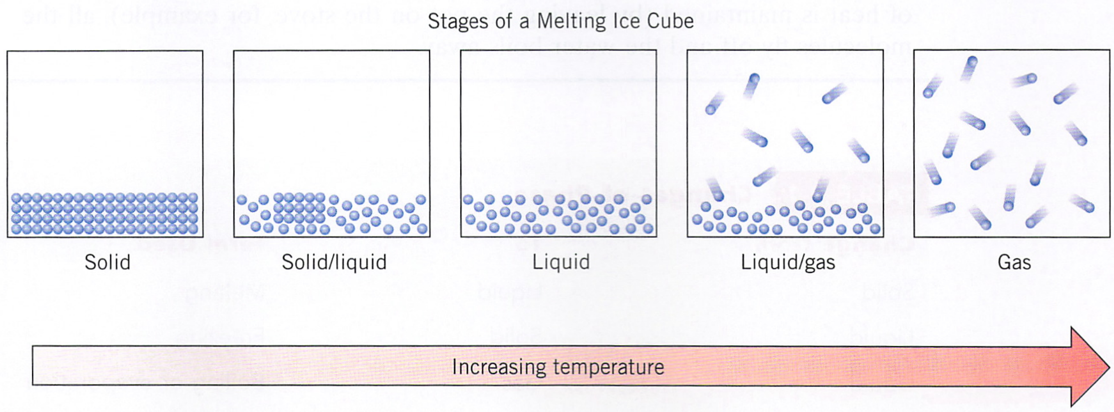
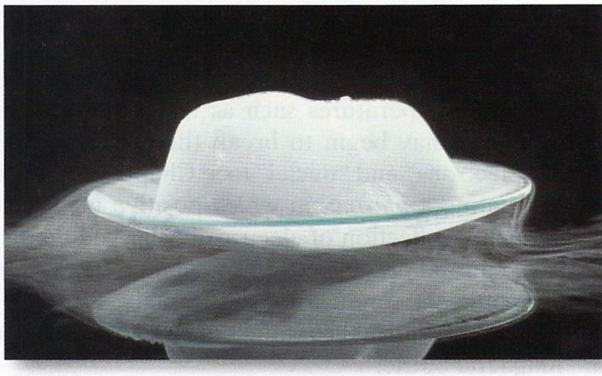


FIGURE 9-11. At the molecular scale, molecules in a solid gain energy as the temperature rises, eventually breaking free of their rigid locations and moving around in a liquid (melting). If the temperature continues to rise, the molecules of liquid gain enough energy to leave the substance altogether, becoming a gas (boiling).



Carbon dioxide in the solid phase (called "dry ice") does not melt into a liquid but goes directly to the gas phase, a process known as sublimation.

This is precisely what happens to the water molecules in an ice cube when it is left out at room temperature and changes into water.

This transformation from solid to liquid is an example of what scientists call a **change of phase:** a process by which a material, without changing its constituent atoms or molecules, changes their arrangement. A variety of familiar changes of phase are listed in Table 9-1.

Develop Your Intuition: Boiling Water Molecules

What does a boiling pot of water look like from an atomic point of view?

The water molecules move around, as already described, and are held in the liquid by relatively weak forces. As the motion of the molecules becomes more and more violent, and as the molecules start moving faster and faster, eventually the fastest molecules acquire enough kinetic energy to tear loose from the surface of the liquid. They fly off into the air as steam, leaving the liquid behind. As boiling continues, molecules from the middle of the pot of water have enough energy to escape the liquid; this is when bubbles form throughout the liquid and the entire pot is in turmoil. Eventually, if the source of heat is maintained (by leaving the pot on the stove, for example), all the molecules fly off and the water boils away.

TABLE 9-1 Changes of Phase

Change from	To	Term Used
Solid	Liquid	Melting
Liquid	Solid	Freezing
Liquid	Gas	Boiling or evaporation
Gas	Liquid	Condensation
Solid	Gas	Sublimation
Gas	Solid	Deposition

THINKING MORE ABOUT

Atoms: Are They Real?

For much of the nineteenth and early twentieth centuries, a mild philosophical debate took place among scientists over the question of whether atoms are real or whether they are merely a useful mathematical construct. With advances in technology and in theoretical understanding over the past 3 centuries, increasingly convincing evidence has mounted for the reality of atoms. Here are some examples of this growing body of evidence.

1. **The behavior of gases** The Swiss physicist Daniel Bernoulli (1700–1782) realized that if atoms are real, they must have mass and velocity, and thus kinetic energy. He successfully applied Newton's second law of motion (force equals mass times acceleration) to atoms to explain the behavior of gases under pressure. Doubling the number of gas particles, or halving the volume, doubles the rate of collisions between the gas particles and the confining walls of its container. This increase in turn doubles the pressure, which equals the force per unit area. Increasing the temperature increases the average velocity of the gas particles and also results in an increase of pressure. Thus the idea of atoms of a gas is consistent with the observed behavior of gases.
2. **Chemical combinations** John Dalton advanced the atomic theory based in part on the law of definite proportions—an empirical law that states that for any given compound, elements combine in a specific ratio of weights. For example, water is always 8 parts oxygen to 1 part hydrogen by weight and carbon dioxide is always 12 parts carbon to 32 parts oxygen by weight. Furthermore, when two elements combine in more than one way, the ratios of weights for the two compounds is a small whole number. Thus, 12 pounds of carbon can combine with either 32 pounds of oxygen or 64 pounds of oxygen. These sorts of regularities are easy to understand in terms of the atomic theory—for example, there are always two hydrogen atoms for every one oxygen atom in water, and oxygen has a mass 16 times that of hydrogen.
3. **Radioactivity** The discovery in 1896 of radioactivity, by which individual atoms emit radiation (see Chapter 26), provided a compelling piece of evidence for the atomic theory. Certain materials called "phosphors" emit a brief flash of light when hit by this radiation. In 1903, upon seeing the irregular twinkling caused by this effect, even the most vocal skeptics of the atomic theory had to reconsider.
4. **Brownian motion** Brownian motion is an erratic, jiggling motion observed in tiny dust particles or pollen grains suspended in water. In 1905, Albert Einstein (1879–1955) demonstrated mathematically that such motions must result from forces—the forces due to random collisions of atoms. Einstein realized that any small object suspended in liquid would be bombarded constantly by moving atoms. At any given moment, purely by chance, more atoms hit one side of the particle than the other. The object is pushed toward the side with fewer collisions. A moment later, however, more atoms strike another surface, and the object changes direction. Over time, Einstein argued, these atomic collisions produce precisely the sort of erratic motion that you can see through a microscope.

   Einstein used the mathematics of statistics to make several testable predictions about how fast and how far the suspended grains would move, based on the hypothesis that the motion was due to collisions with real atoms. French physicist Jean Baptiste Perrin (1870–1942) published careful measurements of Brownian motion in 1909—results that agreed with Einstein's calculations and thus convinced many scientists of the reality of atoms.

   Note that, in spite of the variety of evidence for atoms, to this point all this evidence was indirect. Matter was observed to behave *as if* it were made of atoms, but atoms, themselves, had not been directly observed.

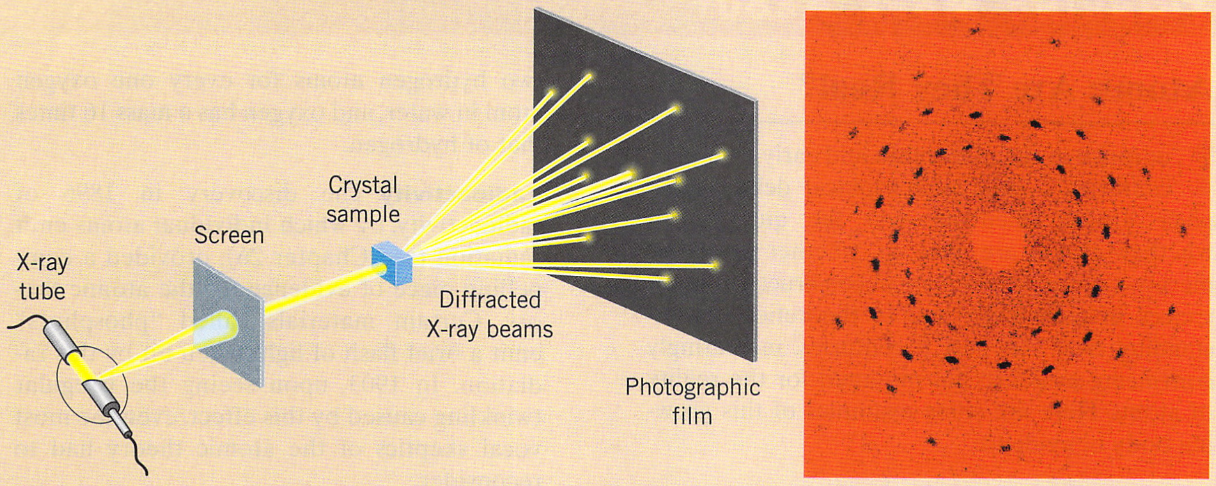


Figure 9-12. The regular atomic structure of a crystal can be revealed by the pattern of X rays that diffract off the crystal.

5. **X-ray crystallography** X-ray crystallography, developed in 1912, convinced any remaining skeptics by demonstrating the sizes (about 10^{-10} meter) and regular arrangements of atoms in crystals. X rays (see Chapter 19) are deflected by crystals in symmetric patterns that reveal the underlying regular atomic structure (Figure 9-12). X rays can't bounce off hypothetical ideas, so these images were further proof that atoms are real physical objects.
6. **Atomic-scale microscopy** In 1980, the first photograph of an individual atom was taken at the University of Heidelberg in Germany. This image was produced by an instrument called a "scanning tunneling microscope," which detects tiny flows of electrons in a microscopic needle placed next to a solid surface. Now, observational studies of individual atoms are undertaken around the world (Figure 9-13).

When in the chain of historical events would you have been willing to believe that atoms are real? When Dalton explained the existence of elements? When Einstein explained Brownian motion? When you were shown a picture such as the one in Figure 9-13? Never? What does it take to make something "real"? And, finally, does it make a difference to science whether or not atoms are real?

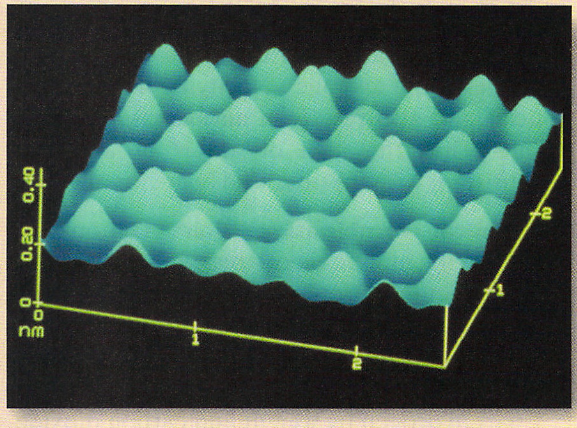


Figure 9-13. Atomic microscope image of individual atoms.

Summary

All matter is formed from tiny objects called **atoms.** The concept of the atom arose in Greek philosophy, but modern atomic theory, based on the observed chemical behavior of materials, began with John Dalton in the early nineteenth century. Chemical **elements** are materials that cannot be broken down into simpler substances by chemical means; each element corresponds to a different type of atom. Atoms combine to form **molecules,** which make up chemical **compounds,** held together by chemical bonds. Atoms or molecules that are found together but that are not bound together chemically are called **mixtures.** The relative masses of atoms can be determined through the use of **Avogadro's principle,** which says that equal volumes of gas at the same temperature and pressure contain the same number of atoms or molecules.

Atoms and molecules can exist in many **phases of matter.** The most common phases are **solid, liquid,** and **gas.** A solid maintains its shape and resists outside forces. Atoms in a solid are locked into place by interatomic (or intermolecular) forces. Liquids maintain their volume but not their shape, and their atoms are free to move around. Gases retain neither shape nor volume, and atoms or molecules in gases interact primarily through collisions.

Changes of phase, including melting, boiling, and freezing, result from changes in the intensity of atomic vibrations that occur when heat is added to or removed from a material.

Key Terms

atom The tiniest particle of matter that retains the chemical properties of an element. (p. 186)

Avogadro's principle The statement that equal volumes of any gas at the same temperature and pressure contain the same number of gas molecules. (p. 188)

change of phase A process by which a material, without changing its constituent atoms or molecules, changes their arrangement. (p. 195)

compound A material that is made up of two or more elements. (p. 187)

element A substance that cannot be broken down into other substances by chemical means. (p. 187)

gas A material that retains neither its shape nor its volume, but expands to fill any container in which it is placed. (p. 193)

liquid A material that maintains a constant volume, but assumes the shape of its container. (p. 192)

mixture A combination of two or more substances in which each substance retains its own chemical identity. (p. 188)

molecule Two or more atoms bound together by electric forces (chemical bonds). (p. 187)

phases of matter The different forms that matter can take; solid, liquid, and gas are the most common. (p. 190)

solid A rigid material that has a definite shape and volume. (p. 190)

thermodynamics The study of heat and energy. (p. 185)

Review

1. Explain Dalton's concept of an atom. How did it differ from the view of the Greeks?
2. Why is the atomic theory of Democritus considered to be philosophy and not science?
3. What is the difference between an atom and a molecule? Give an example of each.
4. How is a bowling ball with Velcro patches on it a good analogy to an atom? If two of these balls are stuck together, what does each component (ball, patches, and groups of such balls stuck together) represent? In what ways is this a bad analogy?
5. What is a compound? How does this differ, if at all, from a molecule?
6. From the perspective of a scientist, what is the critical difference between the Greeks' atomic theory and Dalton's theory?
7. What is a mixture? What role do chemical bonds have in a mixture? In a compound?
8. How do the masses of atoms of the same element compare to one another? Are the masses of atoms of different elements the same or different from one another?
9. What is Avogadro's principle? How was this principle used to determine the relative masses of atoms?
10. What is an atomic mass unit? How is it related to the mass of a hydrogen atom?
11. What are the three phases of matter discussed in this chapter? Do the molecules of a substance change as matter changes to another phase? Do the forces that bind molecules together change? Explain.
12. Define the solid phase of matter. Give an example.
13. What are the similarities and differences between ordinary glass and the structures we know as crystals? Explain.
14. How does heating a solid eventually lead to a liquid phase?
15. What is a polymer? A plastic? How are the molecules arranged in these materials?
16. Classify a crystal, a glass, and a plastic according to the range and direction of their repeating atomic structures.
17. What is a liquid? How are the molecules arranged in this phase of matter?
18. What is a gas? How are molecules and atoms arranged in a gas?

19. What is air (gas) pressure? What does pressure have to do with collisions and Newton's laws? Explain.

20. What are the two most common gases in our atmosphere?

21. What is meant by a change of phase? How does energy affect the change of phase of a substance?

22. What phase changes take place in the following processes: melting, freezing, boiling, condensation, sublimation?

23. Identify three examples of changes of state (other than in water) that occur in your everyday experience.

24. How did Bernoulli's work support the hypothesis that atoms were indeed real and not imaginary constructs?

25. What is the law of definite proportions? Why is it that when two elements combine in more than one way, the ratios of weights for the two compounds are usually small whole numbers?

26. How did the discovery of radioactivity support the reality of the atom? What is Brownian motion and how does it support atomic theory?

27. X-ray crystallography provided some of the first direct evidence of the existence of atoms. How did it provide this evidence?

28. When was the first photograph taken of an atom, and how was this done?

Questions

1. How many atoms are there in a water molecule? How many elements are there in a water molecule?

2. A carbon atom and an iron atom are moving at the same speed. Which atom has more kinetic energy?

3. Fullerenes are large molecules of carbon containing at least 60 carbon atoms. Discovered in 1985, fullerenes take a roughly spherical shape. The carbon atoms are arranged in a way that makes them look like soccer balls. Compare the mass of a C_{60} molecule to the mass of a single gold atom.

4. Based on what you have learned so far, should the techniques used to separate the individual components in a mixture be very different from the methods used to isolate the components that make up compounds? How so?

5. Describe the changes of state for a simple water molecule that goes from a solid to a liquid to a gas from the perspective of the forces that it experiences from its neighboring molecules.

6. Describe the changes of state for a simple water molecule that goes from a solid to liquid to a gas from the perspective of its average kinetic energy.

7. Do you think that there are factors other than temperature that might influence whether a phase change takes place? Specifically, how might the pressure that a material is subjected to influence whether it goes from a liquid to a gas or from a solid to a liquid?

8. What causes the Brownian motion of dust particles? Why aren't larger objects such as baseballs affected by this phenomenon?

9. Two gas-filled tanks have the same volume, temperature, and pressure. They are identical in every way except that one is filled with oxygen (O_2) gas and the other is filled with nitrogen (N_2) gas. Compare the number of gas molecules in each container. Which container weighs more?

10. A 1-liter tank contains 1,000,000,000 oxygen (O_2) molecules and 1,000,000,000 helium (He) atoms. Another tank contains 1,000,000,000 helium (He) atoms. The gases in the tanks have the same pressure and temperature. What is the volume of the tank that contains only helium?

11. Ammonia is a liquid that consists of molecules of (NH_3) (one nitrogen atom with three hydrogen atoms attached). Suppose ammonia is separated into nitrogen (N_2) gas and hydrogen (H_2) gas. If 1 liter of nitrogen is produced, what volume of hydrogen is produced?

12. Diamond and graphite are both solids composed of only carbon atoms. Since all carbon atoms are chemically identical, what do you think accounts for the vastly different properties of graphite and diamond?

13. Which have more average kinetic energy: the molecules in 10 grams of ice or the molecules in 10 grams of steam?

14. If the number of gas atoms in a container is doubled, the pressure of that gas doubles (provided the temperature and the volume of the container remain the same). Explain why the pressure increases in terms of the molecular motion of the gas.

15. Atmospheric pressure is approximately 15 pounds of force per square inch. How much force does the air exert on this side of this page of the book (approximately 100 square inches)? Why isn't it extremely difficult to turn the page?

16. How come crushed ice melts so much faster than an equal mass of ice cubes? (*Hint:* Think about making crushed ice by breaking ice cubes into small pieces. In order to melt ice, heat has to enter it. Where does heat enter the ice?)

Problems

1. The mass of a hydrogen atom is 1.67×10^{-27} kg.
   a. Calculate the weight of a hydrogen atom near the Earth's surface. (Recall from Chapter 5 that $W = m \times g$, where W is the weight, m is the mass, and g is the acceleration due to gravity, 9.8 m/s^2.)
   b. How many hydrogen atoms are there in 1 pound of hydrogen gas?
   c. Suppose that every person in the world (about 6 billion people in all) were employed as an atom counter. Each person would work a 40-hour week and be able to count one atom per second. How long would it take for 6 billion people to count the hydrogen atoms in 1 pound of hydrogen?
2. In gaseous form, oxygen consists of O_2 molecules and hydrogen consists of H_2 molecules. Suppose that instead of H_2 molecules, gaseous hydrogen consisted of H atoms. If this were the case, how many liters of hydrogen gas would be produced for each liter of oxygen gas when water, H_2O, was separated by an electric current?
3. Aluminum electroplating is a process by which aluminum is coated onto a metal object. The object is submerged in a liquid solution containing Al_2O_3 molecules. An electric current breaks up these molecules into oxygen gas and aluminum atoms. The aluminum is attracted to the object to be coated and forms a thin aluminum film on its surface. If a car bumper needs to be plated with 300 grams of aluminum using this electroplating process, what mass of oxygen gas is produced? [Assume masses of 27 atomic mass units (amu) for each aluminum atom and 16 amu for each oxygen atom.]
4. You blow up an ordinary party balloon with air until it has a diameter of 6 inches. Your friend blows up another balloon with helium gas until it has a diameter of 12 inches. Air consists mostly of O_2 and N_2 molecules, while helium gas consists of He atoms. Assume the pressure in each balloon is the same.
   a. Compare the number of helium atoms to the total number of O_2 and N_2 molecules.
   b. Air is about 80% nitrogen and 20% oxygen. Which balloon weighs more and by how much? (*Hint:* Imagine that there are 80 helium atoms in the helium balloon. Calculate the mass, in atomic mass units, of this amount of helium, and then compare to the mass of the corresponding number of oxygen and nitrogen molecules.)

Investigations

1. Which chemical elements do you encounter in more or less pure form in your daily experience? What are the properties of these elements and how are they used?
2. Chromatography is one of the most powerful tools a chemist has to separate out different components within mixtures. It can be used to separate everything from different colored pigments from plants to the various proteins in a cell. Explore the history of chromatography. What are the various types of chromatography and what principles are used to isolate individual components in often complex mixtures.
3. If you had never been told about atoms in science class, what observations might convince you of their existence? What might provide alternative hypotheses to the atomic theory of matter?
4. Investigate the history of extracting metal from metal ores. What techniques are involved in separating out and isolating the metal from compounds, such as iron oxide or bauxite (aluminum oxide)? How do these methods differ from methods that separate out mixtures?
5. In the Thinking More About section on page 197, we present six different significant pieces of evidence that support the once uncertain idea that atoms are indeed real. Pick one of these six pieces of supporting evidence and research the evidence in more detail by taking a closer look at one of the original experiments.
6. PVC, polyvinyl chloride, is a material that is essentially inert in its solid form and ubiquitous in daily life. Investigate the controversy surrounding its production and use by noting the arguments for it and against it, paying attention not only to the solid PVC plastic, but to the vinyl chloride gas used to make it as well. Does the evidence seem to indicate this is a dangerous product to you, or does it seem relatively safe?
7. Amedeo Avogadro, who proposed Avogadro's principle of gas volumes, also estimated the number of atoms that make up a given mass of material. Investigate the history of Avogadro's number and some of the dozen or more ways that scientists have attempted to measure this number.
8. Solids, liquids, and gases are the three common phases of matter in our daily lives, but another phase of matter—plasma—is far more abundant in the universe. (See the Connection on page 195.) Investigate plasmas to discover their unique properties, their distribution in the universe, and their possible technological applications.

WWW Resources

See the *Physics Matters* home page at **www.wiley.com/college/trefil** for valuable web links.

1. **http://cst-www.nrl.navy.mil/lattice/index.html** Information about and representations of 242 crystal lattice structures.
2. **http://chemed.chem.purdue.edu/genchem/topicreview/bp/ch2/mixframe.html** A review of elements, compounds and mixtures at Purdue University.