## CHAPTER OUTLINE



**THIS CHAPTER IN CONTEXT** This chapter has three principal goals. The first is to provide you with an appreciation of the central role that chemistry plays among the sciences. The second is to have you understand the way scientists approach the study of nature and how they construct mental pictures of the microscopic world to explain the results of experimental observations. And third, we will begin to discuss how chemistry views the world around us and how chemists organize the enormous amounts of information they've acquired.

If you've had a prior course in chemistry, perhaps in high school, you're likely to be familiar with many of the topics that we cover in this chapter. Nevertheless, it is important to be sure you have a mastery of these subjects, because if you don't start this course with a firm understanding of the basics, you may find yourself in trouble later on.



In our discussions, we do not assume that you have had a prior course in chemistry. However, we do urge you to study this chapter thoroughly, because the concepts developed here will be used in later chapters.

## 1.1 Chemistry is important for anyone studying the sciences

Much of the quality of life that we and others in the world enjoy today can be traced to the successes of science, and in particular to chemistry. Almost everything we touch or eat or drink or take into our bodies for nutrition or to cure illness bears the marks of chemical research. Synthetic fibers make up much of the fabric of the clothes we wear or form the threads that hold more "natural" fabrics together. Synthetic adhesives are used to bind together natural materials such as wood chips and fibers to yield construction products that are stronger, more stable, and more resistant to decay than traditional wood products. Many foods contain preservatives that retard spoilage, artificial flavors that enhance taste, or substances that improve texture and color. And, of course, drugs developed by pharmaceutical companies cure illnesses today that would have been fatal only a short time ago.

**Chemistry**[1] is a science that studies the composition and properties of **matter,** which we define *as anything that takes up space and has mass*.[2] All of the chemicals that make up tangible things, from rocks to people to pizza, are examples of matter. Chemists seek to answer fundamental questions about how the properties of substances are affected by their compositions. As part of this quest, they seek to learn the way substances change, often dramatically, when they interact with each other in *chemical reactions*. And permeating all of this is a search for knowledge about the basic underlying structure of matter and the

[1]Important terms will be set in bold type to call them to your attention. Be sure you learn their meanings.

[2]Mass is a measure of the amount of matter in an object. It is similar to weight, except that weight refers to the force with which an object of a given mass is attracted by gravity. We discuss mass and the units used to express it in Chapter 3.

**TABLE 1.1 NAMES OF SOME OF THE DIVISIONS OF THE AMERICAN CHEMICAL SOCIETY**

| | |
|---|---|
| Agricultural & Food Chemistry | Environmental Chemistry |
| Agrochemicals | Fertilizer & Soil Chemistry |
| Biochemical Technology | Fluorine Chemistry |
| Biological Chemistry | Fuel Chemistry |
| Business Development & Management | Geochemistry |
| Carbohydrate Chemistry | Industrial & Engineering Chemistry |
| Cellulose, Paper & Textile | Medicinal Chemistry |
| Chemical Health & Safety | Nuclear Chemistry & Technology |
| Chemical Toxicology | Petroleum Chemistry |
| Chemistry & the Law | Polymer Chemistry |
| Colloid & Surface Chemistry | Polymeric Materials: Science & Engineering |
| Computers in Chemistry | Rubber |

forces that determine the properties we are able to observe through our senses. From such knowledge has come the ability to create materials never before found on earth, materials with especially desirable properties that fulfill specific needs of society.

Although you may not plan to be a chemist, some knowledge of chemistry will surely be valuable to you in whatever branch of science you study. In fact, the involvement of chemistry among the various branches of science is evidenced by the names of the various divisions of the American Chemical Society, the largest scientific organization in the world (see Table 1.1).

The reason chemistry holds such a unique place among the sciences is because all things are composed of chemicals. A cricket, for example, is made up of a complex set of chemicals that possess the unique quality we call life. Chemists are interested in these chemicals for their complex structures and the way they behave toward each other. On the other hand, a biologist might wish to study how the cricket metabolizes nutrients and how it derives energy from the process, while an engineer or a physicist might be interested in the mechanics of motion of the limbs of the cricket that allow it to jump. In their activities, the biologist, engineer, and physicist are likely to draw on knowledge gained by chemists. In this way, chemists, biologists, engineers, and physicists may all have interests in the cricket and study the creature from slightly different points of view. Today, in fact, the lines between traditional disciplines such as chemistry and biology have become blurred, so there is little difference, for example, between a molecular biologist and a biochemist.

***A scientist working in a chemical research laboratory.***

## 1.2 The scientific method helps us build models of nature

Chemistry is a dynamic subject, constantly changing as new discoveries are made by researchers who work in university, industrial, and government laboratories. The general approach that these people bring to their work is called the **scientific method.** It is, quite simply, a commonsense approach to developing an understanding of natural phenomena.

### Observations and conclusions are not the same thing

A scientific study normally begins with some questions about the behavior of nature. To search for answers, we begin by examining the work of others who have published in scientific journals. As our knowledge grows, we begin to plan our own experiments, and an essential part of these is the recording of observations. An

**observation** *is a statement that accurately describes something we see, hear, taste, feel, or smell.*

For a scientific observation to be useful, it must be the same no matter who the observer is. Because of this, experiments are performed using well-defined procedures, under carefully controlled conditions, so they are *reproducible.* In this way, others can repeat and confirm the observations. In fact, the ability to obtain the same results when experiments are repeated is what separates a true science from a pseudoscience such as astrology.

When reporting scientific results, it is important not to confuse observations with conclusions.

Observations gathered during an experiment often lead us to make conclusions. A **conclusion** *is a statement that is based on what we think about a series of observations.* To understand the difference between observations and conclusions, consider the following statements about the fermentation of grape juice to make wine:

1. Before fermentation, grape juice is very sweet and contains no alcohol.
2. After fermentation, the grape juice is no longer as sweet and it contains a great deal of alcohol.
3. In fermentation, sugar is converted into alcohol.

Statements 1 and 2 are observations because they describe properties of the grape juice that can be tasted and smelled. Statement 3 is a conclusion because it *interprets* the observations that are available. Now, consider what happens when we add a fourth statement:

4. During fermentation, bubbles of a colorless, odorless gas form in the grape juice.

This is an observation because the bubbles can be seen directly. Making this additional statement doesn't affect observations 1 and 2, but it may very well cause the conclusion (statement 3) to be revised:

3. In fermentation, sugar is converted into alcohol *and a colorless gas.*

Thus, we see that conclusions interpret observations, and when new observations are made, the interpretations may need to be revised.

Observations are statements that directly describe what we measure or perceive and don't need revision when additional data become available.

## Empirical facts lead to scientific laws

The observations we make in the course of performing experiments provide us with **empirical facts**—so named because we learn them by *observing* some physical, chemical, or biological system. These facts are referred to as **data.** For example, if we study the behavior of gases, such as the air we breathe, we soon discover that the volume of a gas depends on a number of factors, including the mass of the gas, its temperature, and its pressure. The observations we record relating these factors are our data.

*Webster's* defines *empirical* as "pertaining to, or founded upon, experiment or experience."

One of the goals of science is to organize facts so that relationships or generalizations among the data can be established. For instance, one generalization we would make from our observations is when the temperature of a gas is held constant, squeezing the gas into half its original volume causes the pressure of the gas to double. If we were to repeat our experiments many times with numerous different gases, we would find that this generalization is uniformly applicable to all of them. Such a broad generalization, based on the results of many experiments, is called a **law** or **scientific law.**

We would say that the pressure of the gas is inversely proportional to its volume—the smaller the volume, the larger the pressure.

Laws are often expressed in the form of mathematical equations. For example, if we represent the pressure of a gas by the symbol $P$ and its volume by $V$, the inverse relationship between pressure and volume can be written as

$$P = \frac{C}{V}$$

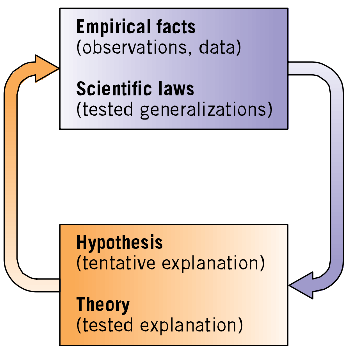
where $C$ is a proportionality constant. (We will discuss gases and the laws relating to them in greater detail in Chapter 11.)

## Hypotheses and theories are models of nature



As useful as they may be in summarizing the results of experiments, laws can only state what happens. They do not explain *why* substances behave the way they do. *Why,* for example, are gases so easily compressed to a smaller volume? More specifically, *what must gases be like at the most basic, elementary level for them to behave as they do*? Answering such questions when they first arise is no simple task and requires much speculation. But gradually, scientists build mental pictures, called **theoretical models,** that enable them to explain observed laws.

In the development of a theoretical model, tentative explanations, called **hypotheses,** are formed. These explanations are then tested by performing experiments that test predictions derived from the model. Sometimes the results show the model is wrong. When this happens, the model must be abandoned or, as often happens, modified to account for the new data. Eventually, if the model survives repeated testing, it gradually achieves the status of a theory. *A* **theory** *is a tested explanation of the behavior of nature.* Most useful theories are broad, with many far-reaching and subtle implications. It is impossible, however, to perform every test that might show a theory to be wrong, so we can never be *absolutely* sure a theory is correct.




***The scientific method is cyclical.*** Observations suggest explanations, which suggest new experiments, which suggest new explanations, and so on.

Many breakthrough discoveries in science have come about by accident.

The sequence of steps just described—observation, explanation through the creation of a theoretical model, and the testing of the model by additional experiments—constitutes the **scientific method.** Despite its name, this method is not used only by those who call themselves scientists. An auto mechanic follows essentially the same steps when fixing your car. First, tests are performed (*observations* are made) that enable the mechanic to suggest the probable cause of the problem (*a hypothesis*). Then parts are replaced and the car is checked to see whether the problem has been solved (*testing the hypothesis by experiment*). In short, we all use the scientific method as much by instinct as by design.

From the preceding discussion you may get the impression that scientific progress always proceeds in a dull, orderly, and stepwise fashion. This isn't true; science is exciting and provides a rewarding outlet for cleverness and creativity. Luck, too, sometimes plays an important role. For example, in 1828 Frederick Wöhler, a German chemist, was heating a substance called ammonium cyanate in an attempt to add support to one of his hypotheses. His experiment, however, produced an unexpected substance, which out of curiosity he analyzed and found to be urea (a component of urine). This was an exciting discovery because it was the first time anyone had knowingly made a substance produced only by living creatures from a chemical not having a life origin. The fact that this could be done led to the beginning of a whole branch of chemistry called *organic chemistry.* Yet, had it not been for Wöhler's curiosity and his application of the scientific method to his unexpected results, the significance of his experiment might have gone unnoticed.

As a final note, it is significant that the most spectacular and dramatic changes in science occur when major theories are proved to be wrong. Although this happens only rarely, when it does occur, scientists are sent scrambling to develop new theories, and exciting new frontiers are opened.

## The atomic theory is a model of nature

Virtually every scientist would agree that the most significant theoretical model of nature ever formulated is the atomic theory. According to this theory, which we will discuss further in Section 1.5, all chemical substances are composed of tiny particles that we call **atoms.** Individual atoms combine in diverse ways to form more complex particles called **molecules.** Consider, for example, the substance water. Experimental evidence suggests that water molecules are each

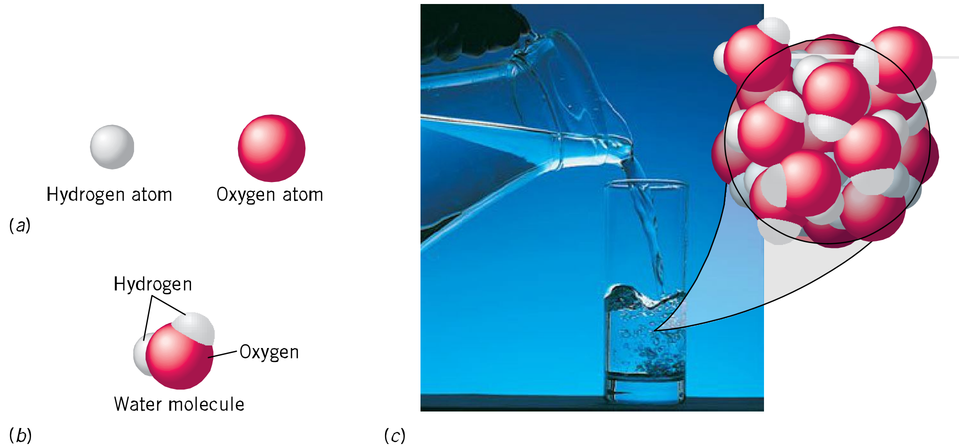



**FIGURE 1.1** ***Atoms combine to form molecules.*** Illustrated here are molecules of water, each of which consists of one atom of oxygen and two atoms of hydrogen. (*a*) Colored spheres are used to represent individual atoms, gray for hydrogen and red for oxygen. (*b*) A drawing that illustrates the shape of a water molecule. (*c*) A glass of liquid water contains an enormous number of tiny water molecules jiggling about.

composed of two atoms of hydrogen and one of oxygen. To aid in our understanding and to help visualize how atoms combine, we often use drawings such as Figure 1.1, which is an attempt to depict a collection of water molecules. Notice that we show each molecule as composed of the same atoms (hydrogen and oxygen) in the same proportions. In a similar fashion, each of the different chemicals we find around us is composed of atoms of various kinds in specific combinations.

The concept of atoms and molecules enables us to visualize what takes place when atoms combine in various ways. As you will see, it also enables us to understand, explain, and sometimes predict a wide range of observations concerning the behavior of nature. To help us, we will frequently use drawings to illustrate molecules; Figure 1.2 shows some of the ways molecules can be represented.

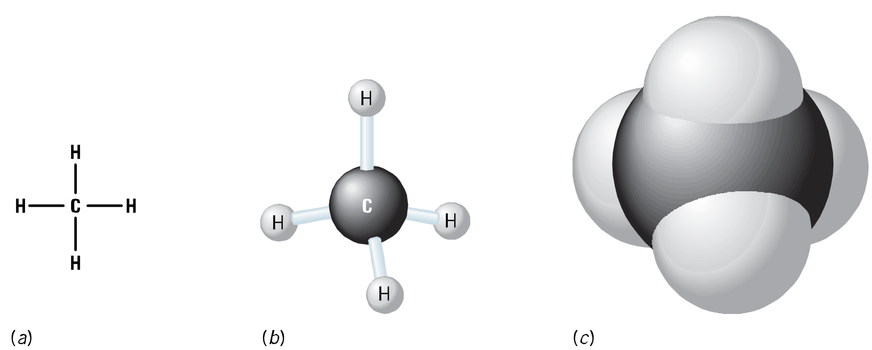



**FIGURE 1.2** ***Some of the different ways that structures of molecules are represented.*** (*a*) A structure using chemical symbols to stand for atoms and dashes to indicate how the atoms are connected to each other. The molecule is methane, the substance present in natural gas that fuels stoves and Bunsen burners. A methane molecule is composed of one atom of carbon (C) and four atoms of hydrogen (H). (*b*) A *ball-and-stick model* of methane. The dark gray ball is the carbon atom and the light gray balls are hydrogen atoms. (*c*) A *space-filling model* of methane that shows the relative sizes of the C and H atoms. Ball-and-stick and space-filling models are used to illustrate the three-dimensional shapes of molecules.

We use the term *macroscopic* to mean the world we observe with our senses, whether it be in the laboratory or the world we encounter in our day-to-day living.

We will expand on the atomic model as we proceed in our discussions, and we will frequently make the connection between what we physically observe in our large, *macroscopic* world and what we believe takes place in the tiny, submicroscopic world of atoms and molecules. Learning to recognize these connections should be one of your major goals in studying this course.

## 1.3 Properties of materials can be classified in different ways

If you had lost your chemistry book and were asked to describe it, you would probably list its size, color, and the printing on its cover. These are the characteristics that books have that help you identify them and distinguish among them. Similarly, in chemistry we use the characteristics, or *properties,* of materials to identify them and to distinguish one kind from another. To help organize our thinking, we classify properties into different types.

### Properties can be classified as physical or chemical

One way to classify properties is based on whether or not the chemical composition of an object is changed by the act of observing the property.

#### Physical properties are observed without changing the chemical makeup of a substance

*A* **physical property** *is one that can be observed without changing the chemical makeup of a substance.* For example, one of the physical properties of gold is that it is yellow. The act of observing this property (color) doesn't change the chemical makeup of the gold. Neither does observing that gold conducts electricity, so electrical conductivity is another physical property of gold.

Sometimes, observing a physical property does lead to a change. Melting point is an example. To measure this property, we observe the temperature at which melting begins. This does not lead to a change in chemical composition, however. For instance, both ice and liquid water are composed of water molecules; melting just permits molecules that are locked in place in the solid to become mobile and move about in the liquid.

***Liquid water and ice are both composed of water molecules.*** Melting the ice cube doesn't change the chemical composition of the molecules.

The change we observe during melting is a **physical change** because *it is not accompanied by a change in chemical makeup.* Another physical change is observed when a substance dissolves in a liquid (for instance, sugar dissolving in water). This ability of sugar to dissolve in water is a physical property because the act of dissolving the sugar doesn't alter its chemical composition. Figure 1.3 illustrates how the molecules of sugar and water simply intermingle when the sugar dissolves. By evaporating the water we can show that the chemical makeup of the sugar has not been affected; the sugar is recovered chemically unchanged. Because the sugar isn't altered chemically as it dissolves, forming the solution is a physical change.

#### A chemical property describes a chemical change

Chemistry is especially concerned with learning and understanding changes that alter the chemical makeup of substances, changes that we call chemical reactions. In a **chemical reaction,** chemicals interact with each other to form entirely *different* substances with different properties. An example is the rusting of iron, which involves a chemical reaction between iron, oxygen, and water. Iron is a metallic solid that is attracted by a magnet. Oxygen is one of the components of air and is a gas. Water, of course, is a liquid. When these react to form rust, the product no longer looks like iron, oxygen, or water. It is a brown solid that doesn't look at all like a metal and it is not attracted by a magnet. (See Figure 1.4.)

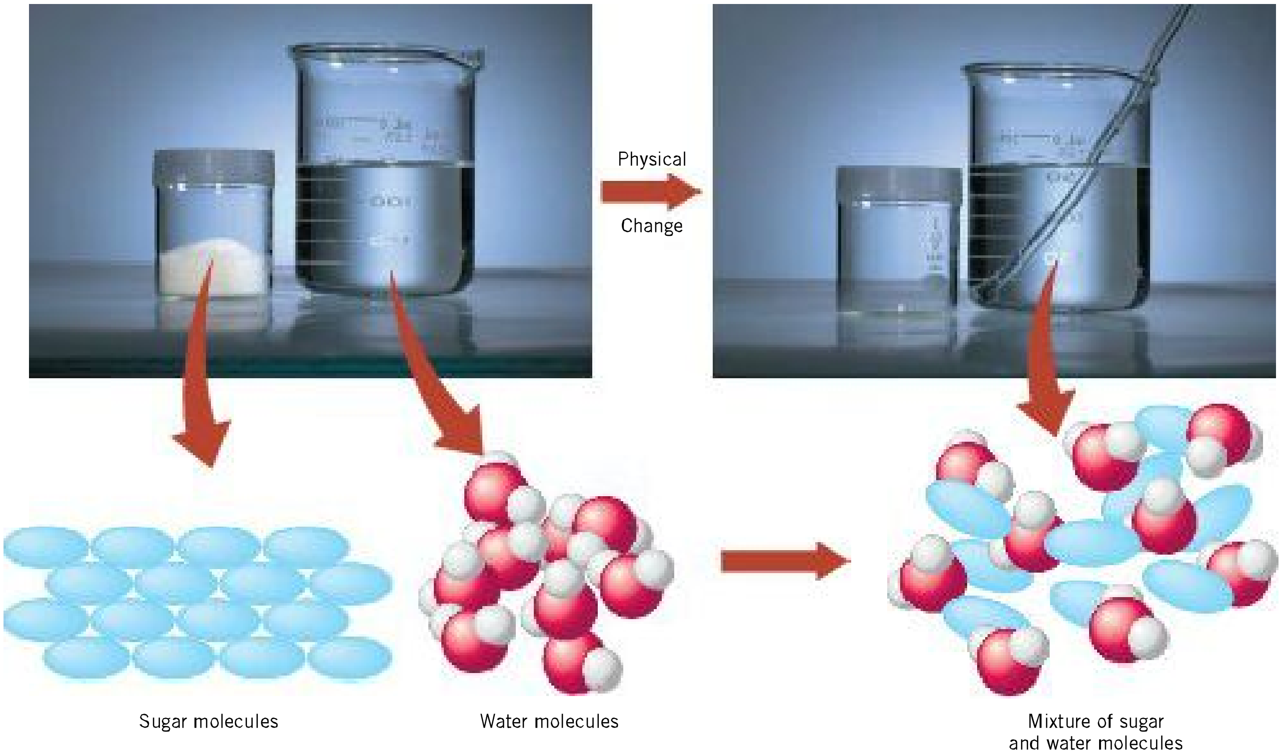



**FIGURE 1.3** ***Formation of a solution of sugar in water.*** As the sugar mixes with the water, sugar molecules (shown here in a very simplified way) mingle with water molecules. The chemical makeup of the individual sugar and water molecules does not change, however, so no chemical reaction has occurred.

*A* **chemical property** *describes a* **chemical change** *(chemical reaction) that a substance undergoes.* Thus, one chemical property of iron is that it forms rust in the presence of oxygen and moisture. When we observe this property, the reaction changes the iron, oxygen, and water into rust, so after we've made the observation we no longer have the same substances as before. Another example is the change that occurs when we melt sugar in a pan and heat it to a high temperature. We observe that the color of the sugar darkens as it begins to decompose into carbon and water. The decomposition of sugar at high temperatures is a chemical property, because the only way we can observe it is by having the chemical reaction occur. It is a reaction that leads to a permanent change in chemical composition, which is not reversed by cooling the sugar to room temperature.

When we observe a chemical property of a substance, the substance undergoes a reaction and changes into something else. When we observe a physical property, the substance is not changed chemically.

## Properties can also be classified as intensive or extensive

Another way of classifying a property is according to whether or not the property depends on the size of the sample under study. For example, the volumes of two different pieces of gold can be different, but both have the same characteristic shiny yellow color, both conduct electricity, and both will begin to melt if heated to the same temperature. Volume is said to be an **extensive property**—*a property that depends on sample size.* Color, electrical conductivity, melting point (and boiling point) are examples of **intensive properties**—*properties that are independent of sample size.*[3]

Volume is an extensive physical property. Color is an intensive physical property.

[3]Color can often be a useful property for identification, but there are instances where you can be fooled, particularly when particle size is very small. For example, silver is a white metal with a high luster; however, in a very finely divided state, as in the image on black-and-white photographic film or paper, metallic silver appears black.

**FIGURE 1.4** ***Chemical reactions cause changes in composition.*** Here we see a coating of rust that has formed on iron nuts and bolts. The properties and chemical composition of the rust are entirely different from those of the iron.

### Some kinds of properties are better than others for identifying substances

A job chemists are often called upon to perform is chemical analysis. They're asked, "What is a particular sample composed of?" To answer such a question, the chemist relies on the properties of the chemicals that make up the sample.

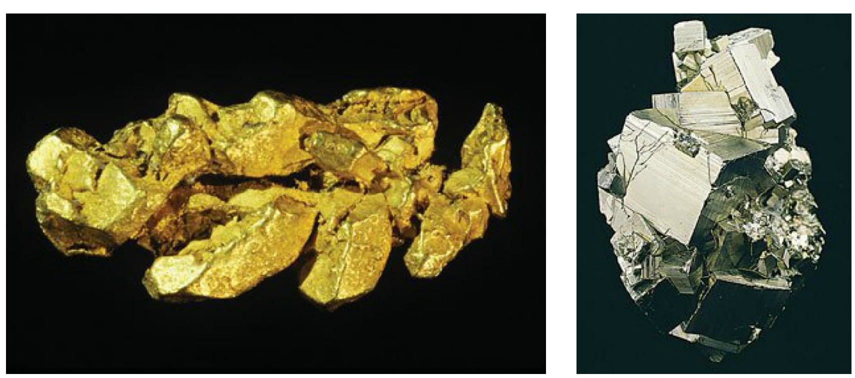
For identification purposes, intensive properties are more useful than extensive ones because every sample of a given substance exhibits the same set of intensive properties. For instance, if you were asked to decide whether a particular liquid sample was water, measuring its volume wouldn't help in your identification because volume is not an unvarying property of a substance. By taking appropriate amounts, it is possible for *any* liquid to have a given volume. However, if you observe that the liquid is clear and colorless and then by measurement find that it freezes at 0 °C and boils at 100 °C, you might be fairly confident that the liquid is water.[4] This is because these are properties that all samples of water have in common. On the other hand, if the liquid *did not* freeze and boil at 0 °C and 100 °C, respectively, then you would be very confident the liquid was *not* water.

Color, freezing point, and boiling point are examples of physical properties that can help us identify substances. Chemical properties are also intensive properties and also can be used for identification. For example, gold miners were able to distinguish between real gold and fool's gold (a mineral also called pyrite, Figure 1.5) by heating the material in a flame. Nothing happens to the gold, but the pyrite sputters, smokes, and releases bad-smelling fumes because of its ability, when heated, to react chemically with oxygen in the air.

## 1.4 Materials are described by their properties

It's natural for us to look for threads of organization among apparently unrelated facts. When we examine the myriad of different materials that surround us, we therefore seek to classify them, and one way to do this is according to their properties.

[4]We usually use the Celsius temperature scale in the sciences. We discuss this in more detail in Chapter 3.



(*a*) (*b*)

**FIGURE 1.5** ***Identification of substances by their properties.*** Gold and the mineral pyrite (also called iron pyrite) have similar colors, which is why some miners mistook pyrite for gold. (*a*) A nugget of pure gold. (*b*) A sample of iron pyrite. The color of the mineral accounts for its nickname, "fool's gold."

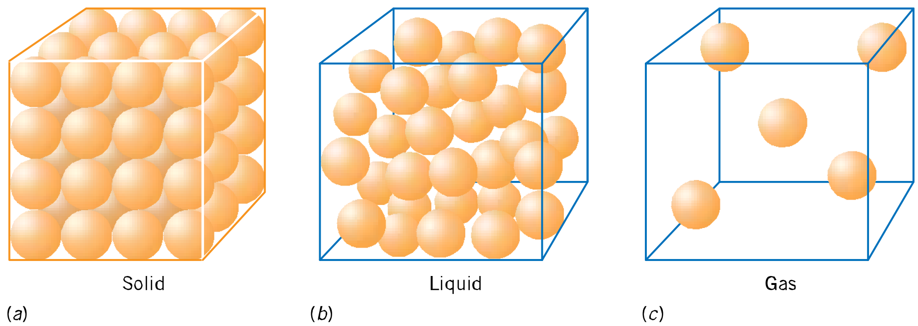



**FIGURE 1.6** ***Solid, liquid, and gaseous states of matter as viewed by the atomic model of matter.*** (*a*) In a solid, the particles are tightly packed and cannot move easily. (*b*) In a liquid, the particles are still close together but can move past one another. (*c*) In a gas, the particles are far apart with much empty space between them.

## Solids, liquids, and gases are states of matter

As you probably know, ice, liquid water, and steam are *not* different substances. Although they have quite different appearances and physical properties, they are just different forms of the same substance, water. **Solid, liquid,** and **gas** are the most common **states of matter.** As with water, most substances are able to exist in all three of these states, and the state we observe generally depends on the temperature.

The obvious properties of solids, liquids, and gases can be interpreted at a submicroscopic level according to the different ways the individual atomic-size particles are organized (Figure 1.6). In a solid, they are packed tightly together and are unable to move about, so solids are rigid. In a liquid, the particles are still close together, but they are capable of moving past each other and a liquid is therefore able to flow. In gases, the particles are far apart with much empty space between them. This makes it easy to see through gases and also explains why they are so easily compressed; pushing the particles together just reduces the empty space between them.

## Elements cannot be decomposed by chemical means

When a chemical reaction changes one substance into two or more others, a **decomposition** has occurred. For example, if we pass electricity through molten (melted) sodium chloride (salt), the silvery metal, sodium, and the pale green gas, chlorine, are formed. In this example, we have decomposed sodium chloride into two simpler substances. No matter how we try, however, sodium and chlorine cannot be decomposed further by chemical reactions into still simpler substances that can be stored and studied.

In chemistry, *substances that cannot be decomposed into simpler materials by chemical reactions are called* **elements.** Sodium and chlorine are two examples. Others you may be familiar with include iron, chromium, lead, copper, aluminum, sulfur, and carbon (as in charcoal). Some elements are gases at room temperature, including chlorine, oxygen, hydrogen, nitrogen, and helium. Elements are the simplest forms of matter that chemists work with directly. All more complex substances are composed of elements in various combinations.

### Chemical symbols are used to identify elements

So far, scientists have discovered 90 existing elements in nature and have made 23 more, for a total of 113. Each element is assigned a unique **chemical symbol,** which can be used as an abbreviation for the name of the element. As we will dis-

**TABLE 1.2 ELEMENTS THAT HAVE SYMBOLS DERIVED FROM THEIR LATIN NAMES**

| Element | Symbol | Latin Name | Element | Symbol | Latin Name |
|---|---|---|---|---|---|
| Sodium | Na | Natrium | Gold | Au | Aurum |
| Potassium | K | Kalium | Mercury | Hg | Hydrargyrum |
| Iron | Fe | Ferrum | Antimony | Sb | Stibium |
| Copper | Cu | Cuprum | Tin | Sn | Stannum |
| Silver | Ag | Argentum | Lead | Pb | Plumbum |

cuss in the next chapter, chemical symbols are also used to stand for atoms of elements when we write chemical formulas. In most cases, the symbol is formed from one or two letters of the English name for the element. For instance, the symbol for carbon is C, for bromine it is Br, and for silicon it is Si. For some elements, the symbols are derived from the Latin names given to those elements long ago. Table 1.2 contains a list of elements whose symbols come to us in this way.[5]

Latin was the universal language of science in the early days of chemistry.

Regardless of the origin of the symbol, the first letter is always capitalized and the second letter, if there is one, is always written lowercase. Thus, the symbol for copper is Cu, not CU. Be careful to follow this rule so you can avoid confusion between such symbols as Co (cobalt) and CO (carbon monoxide). The names and chemical symbols of the elements are given on the inside front cover of the book. Although the list may seem long, many elements are rare, and we will be most interested in only a relatively small number of them.



**PRACTICE EXERCISE 1:** As you will learn in Chapter 2, chemical symbols are used to write formulas for compounds. For each of the following, identify the elements present on the basis of their chemical symbols (the meaning of subscripts will be made clear in Chapter 2). (a) $Fe_2O_3$ (rust), (b) $Na_3PO_4$ (TSP, a cleaning agent), (c) $Al_2O_3$ (the major component of the gem, ruby), (d) $CaCO_3$ (found in seashells)

## Compounds are composed of two or more elements in fixed proportions

By means of chemical reactions, elements combine in various *specific proportions* to give all the more complex substances in nature. Thus, hydrogen and oxygen combine to form water, and sodium and chlorine combine to form sodium chloride (common table salt). Water and sodium chloride are examples of compounds. A **compound** *is a substance formed from two or more* ***different elements*** *in which the elements are always combined in the same fixed (i.e., constant) proportions by mass.* For example, if any sample of pure water is decomposed, the mass of oxygen obtained is *always* eight times the mass of hydrogen. Similarly, when hydrogen and oxygen react to form water, the mass of oxygen consumed is always eight times the mass of hydrogen, never more and never less.

Water and salt must be more complex than elements because they can be decomposed to elements.

In our description of the makeup of a compound, there is a subtle but significant point to be understood. For example, we say that the compound carbon dioxide, a substance formed in the combustion of many fuels, is *composed of* carbon and oxygen. However, in this compound these two elements are not present in the same form as we find them in their pure states. We can see this by comparing the properties of the compound with those of the elements from which it's formed. Ordinarily, carbon is found as a black solid, as in coal and charcoal. But at room temperature, carbon dioxide isn't a solid, it's a colorless gas. Oxygen is also a gas,

[5]The symbol for tungsten is W, from the German name *Wolfram*. This is the only element whose symbol is neither related to its English name nor derived from its Latin name.