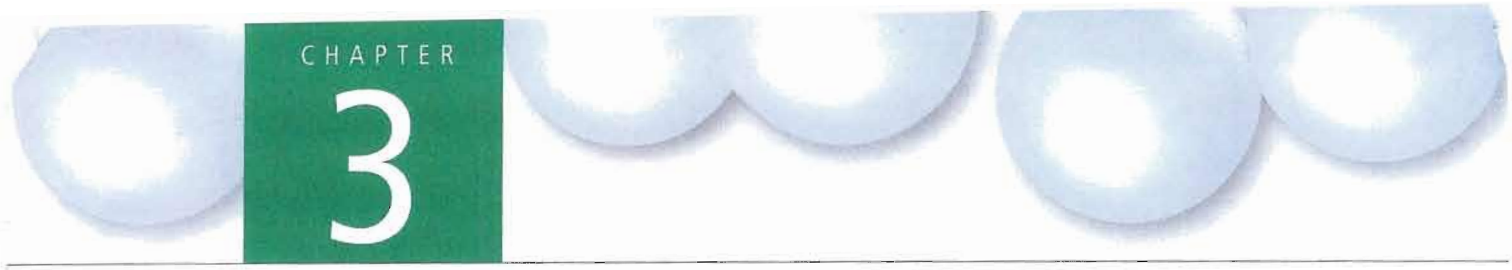
CHAPTER 3



Matter and Energy

◀ Everything that you can see in this room is made of matter. As chemists, we are interested in how the differences between different kinds of matter are related to the differences between the molecules and atoms that compose them. The molecular structures shown here are water molecules on the left and carbon atoms in graphite on the right.

"Thus, the task is, not so much to see what no one has yet seen; but to think what nobody has yet thought, about that which everybody sees."

Erwin Schrödinger (1887–1961)

3.1 In Your Room

Look around your room—what do you see? You might see your desk, your bed, or a glass of water. Maybe you have a window and can see trees, grass, or mountains. You can certainly see this book and possibly the table it sits on. What are these things made of? They are all made of matter, which we will define more carefully shortly. For now, know that all you see is matter—your desk, your bed, the glass of water, the trees, the mountains, and this book. Some of what you don't see is matter as well. For example, you are constantly breathing air, which is also matter, into and out of your lungs. You feel the matter in air when you feel wind on your skin. Virtually everything is made of matter.

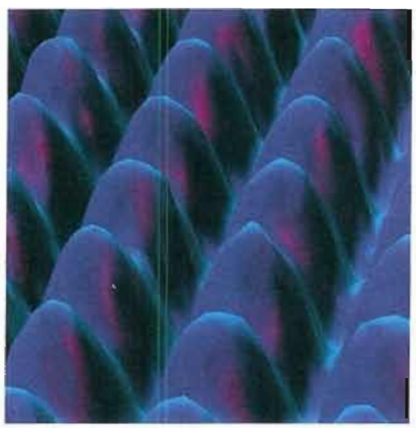
Think about the differences between different kinds of matter. Air is different from water, and water is different from wood. One of our first tasks as we learn about matter is to identify the similarities and differences among different kinds of matter. How are sugar and salt similar? How are air and water different? Why are they different? Why is a mixture of sugar and water similar to a mixture of salt and water but different from a mixture of sand and water? As students of chemistry, we are particularly interested in the similarities and differences between various kinds of matter and how these reflect the similarities and differences between their component atoms and molecules. We want to understand the connection between the macroscopic world and the molecular one.

3.2 What Is Matter?

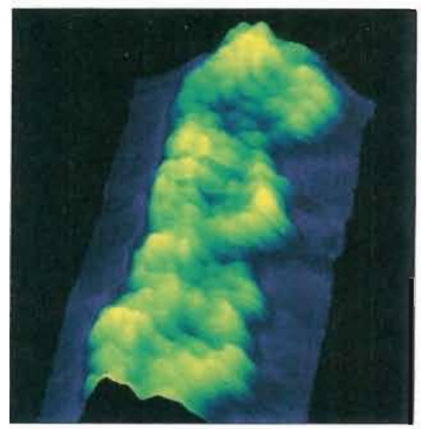
Matter is defined as anything that occupies space and has mass. Some types of matter—such as steel, water, wood, and plastic—are easily visible to our eyes. Other types of matter—such as air or microscopic dust—are impossible to see without magnification. Matter may sometimes appear smooth and

(a) (b)

▲ **Figure 3.1 Atoms and molecules** All matter is ultimately composed of atoms. **(a)** In some substances, such as aluminum, the atoms exist as independent particles. **(b)** In other substances, such as alcohol, several atoms bond together in well-defined structures called molecules.



▲ **Figure 3.2 Scanning tunneling microscope image of nickel atoms** A scanning tunneling microscope (STM) creates an image by scanning a surface with a tip of atomic dimensions. It can distinguish individual atoms, as in this photo. (*Source:* Reprint Courtesy of International Business Machines Corporation, copyright © International Business Machines Corporation.)



▲ **Figure 3.3 Scanning tunneling microscope image of a DNA molecule** DNA is the hereditary material that encodes the operating instructions for most cells in living organisms.

continuous, but actually it is not. Matter is ultimately composed of **atoms**, tiny particles too small to see (▲ Figure 3.1a). In many cases, these atoms are bonded together to form **molecules**, (▲ Figure 3.1b) two or more atoms joined to one another in specific geometric arrangements. Recent advances in microscopy have allowed us to image the atoms (▲ Figure 3.2) and molecules (▲ Figure 3.3) that compose matter, sometimes with stunning clarity.

3.3 Classifying Matter According to Its State: Solid, Liquid, and Gas

The common **states of matter** are **solid**, **liquid**, and **gas** (▶ Figure 3.4). In solid matter, atoms or molecules pack close to each other in fixed locations. Although neighboring atoms or molecules in a solid may vibrate or oscillate,

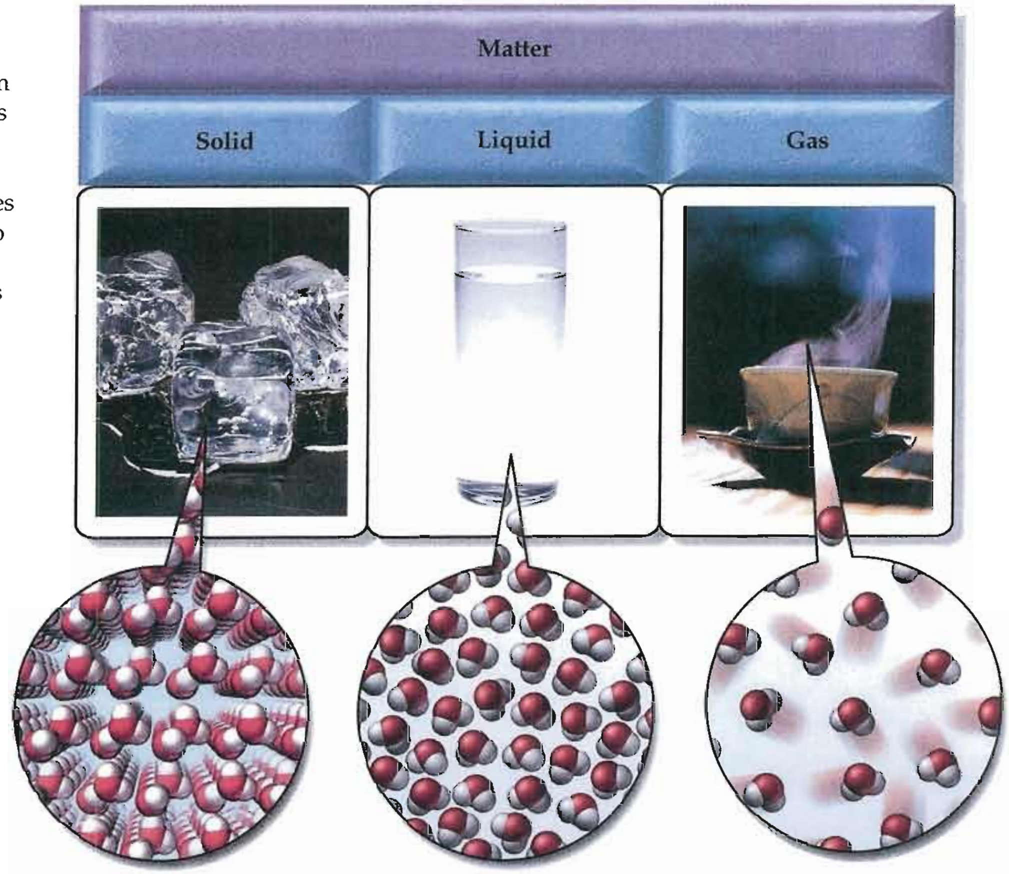


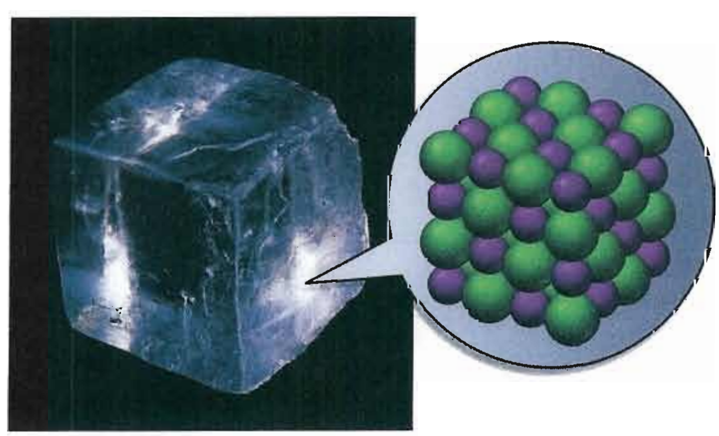
Figure 3.4 Three states of matter Water exists as ice (solid), water (liquid), and steam (gas). In ice, the water molecules are closely spaced and do not move relative to one another. In liquid water, the water molecules are closely spaced but are free to move around and past each other. In steam, water molecules are separated by large distances and do not interact significantly with one another.

they do not move around each other, giving solids their familiar fixed volume and rigid shape. Ice, diamond, quartz, and iron are all good examples of solid matter. Solid matter may be **crystalline**, in which case its atoms or molecules arrange in geometric patterns with long-range, repeating order (◀ Figure 3.5a), or it may be **amorphous**, in which case its atoms or molecules do not have long-range order (Figure 3.5b). Good examples of *crystalline* solids include salt (▼ Figure 3.6) and diamond; the well-ordered, geometric shapes of salt and diamond crystals reflect the well-ordered geometric arrangement of their atoms. Good examples of *amorphous* solids include glass, rubber, and plastic.

(a) Crystalline solid

(b) Amorphous solid

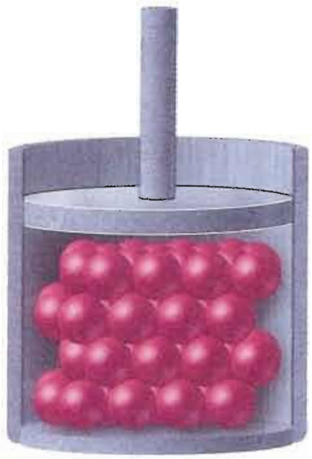
▲ **Figure 3.5 Types of solid matter** **(a)** In a crystalline solid, atoms or molecules occupy specific positions to create a well-ordered, three-dimensional structure. **(b)** In an amorphous solid, atoms do not have any long-range order.



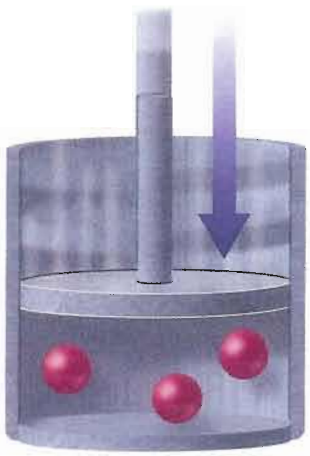
▲ **Figure 3.6 Salt: a crystalline solid** Sodium chloride is an example of a crystalline solid. The well-ordered, cubic shape of salt crystals is due to the well-ordered, cubic arrangement of its atoms.

In liquid matter, atoms or molecules are close to each other (about as close as in a solid) but are free to move around and by each other. Like solids, liquids have a fixed volume because their atoms or molecules are in close contact. Unlike solids, however, liquids assume the shape of their container because the atoms or molecules are free to move relative to one another. Water, gasoline, alcohol, and mercury are all good examples of liquid matter.

In gaseous matter, atoms or molecules are separated by large distances and are free to move relative to one another. Since the atoms or molecules that compose gases are not in contact with one another, gases are **compressible** (◀ Figure 3.7). When you inflate a bicycle tire, for example, you push more atoms and molecules into the same space, compressing them and making the tire harder. Gases always assume the shape and volume of their containers. Good examples of gases include oxygen, helium, and carbon dioxide. The properties of solids, liquids, and gases are summarized in Table 3.1.



Solid–not compressible



Gas–compressible

▲ **Figure 3.7 Why gases are compressible** Since the atoms or molecules that compose gases are not in contact with one another, gases are compressible.

TABLE 3.1 Properties of Liquids, Solids, and Gases

State	Atomic/ Molecular Motion	Atomic/ Molecular Spacing	Shape	Volume	Compressibility
solid	oscillation/ vibration about fixed point	close together	definite	definite	incompressible
liquid	free to move relative to one another	close together	indefinite	definite	incompressible
gas	free to move relative to one another	far apart	indefinite	indefinite	compressible

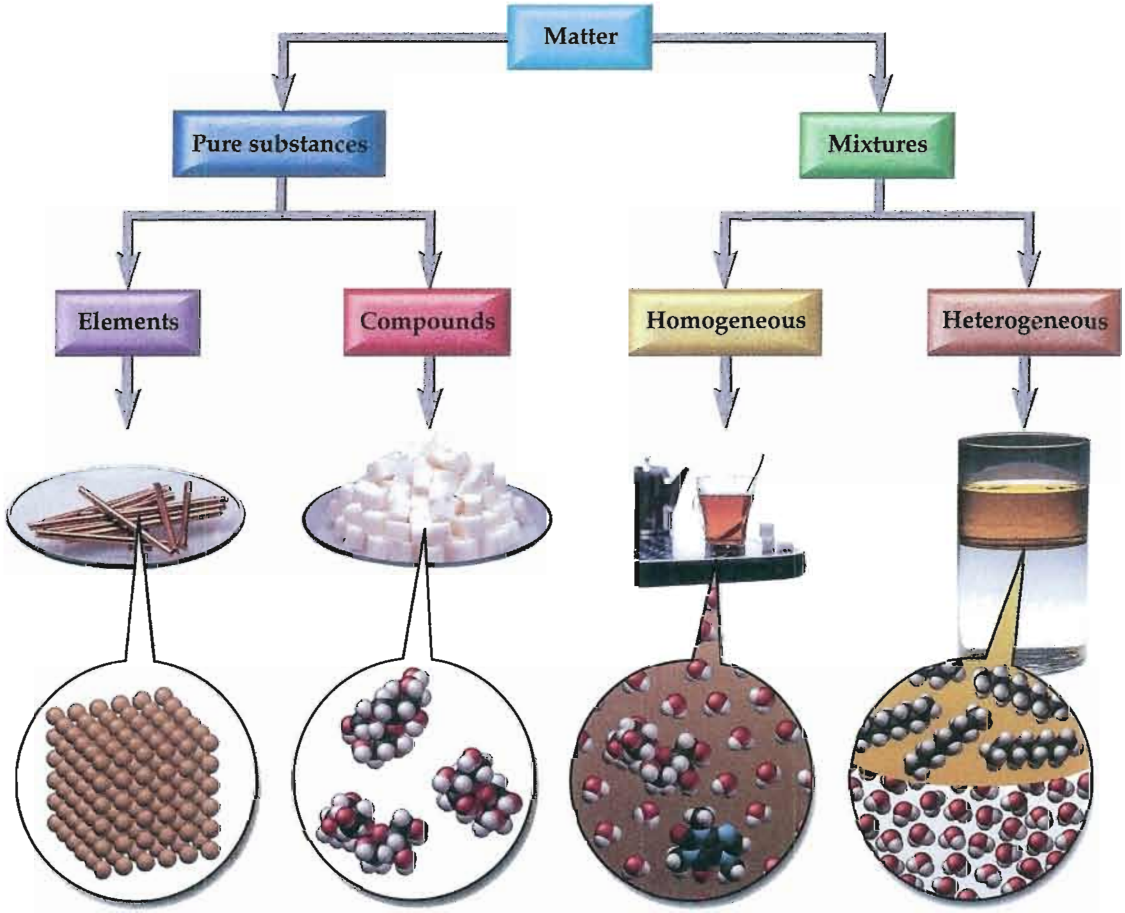
3.4 Classifying Matter According to Its Composition: Elements, Compounds, and Mixtures

In addition to classifying matter according to its state, we can classify it according to its composition (▶ Figure 3.8). Matter may be either a **pure substance**, composed of only one type of atom or molecule, or a **mixture**, composed of two or more different types of atoms or molecules combined in variable proportions.

▲ Helium is a pure substance composed only of helium atoms.

Pure substances are those composed of only one type of atom or molecule. Helium and water are both good examples of pure substances. The atoms that compose helium are all helium atoms, and the molecules that compose water are all water molecules—no other atoms or molecules are mixed in.

Pure substances can themselves be divided into two types: elements and compounds. Copper is a good example of an **element**, a substance that cannot be broken down into simpler substances. The graphite in pencils is also an element—carbon. No chemical transformation can decompose graphite into simpler substances; it is pure carbon. All known elements are listed in the periodic table in the inside front cover of this book and in alphabetical order on the inside back cover of this book.

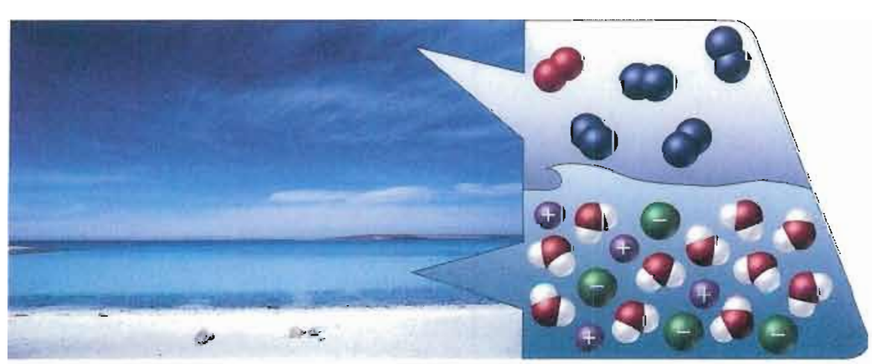


▲**Figure 3.8** **Classification of matter** Matter may be a pure substance or a mixture. A pure substance may be either an element (such as copper) or a compound (such as sugar), and a mixture may be either homogeneous (such as sweetened tea) or heterogeneous (such as hydrocarbon and water).

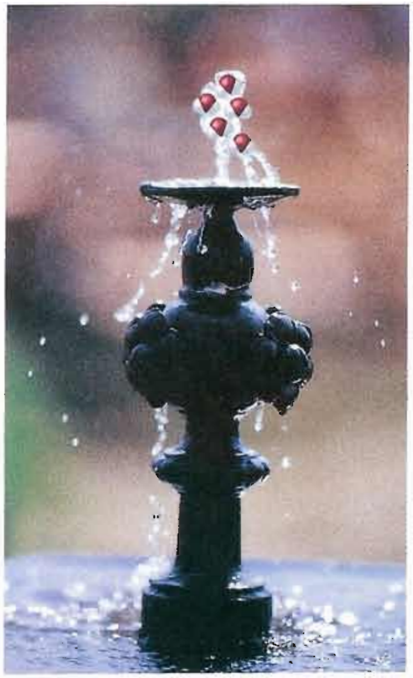
A compound is composed of different atoms that are chemically united (bonded). A mixture is composed of different substances that are not chemically united, but simply mixed together.

A pure substance can also be a **compound**, a substance composed of two or more elements in fixed definite proportions. Compounds are more common than pure elements because most elements are chemically reactive and combine with other elements to form many different compounds. Water, table salt, and sugar are good examples of compounds; they can all be decomposed into simpler substances. For example, if you heat sugar on a pan over a flame, you decompose it into carbon (an element) and gaseous water (a new compound). The black substance left on your pan after burning is the carbon; the water escapes into the air as steam.

The majority of matter that we encounter is in the form of mixtures. A cup of apple juice, a flame, salad dressing, and soil are all examples of mixtures;



▶ Air and seawater are good examples of mixtures. Air contains primarily nitrogen and oxygen. Seawater contains primarily salt and water.



▲ Water is a pure substance composed only of water molecules.

they contain several substances with proportions that vary from one sample to another. Other common mixtures include air, seawater, and brass. Air is a mixture composed primarily of nitrogen and oxygen gas, seawater is a mixture composed primarily of salt and water, and brass is a mixture composed of copper and zinc. Each of these mixtures can have different proportions of its constituent components. For example, metallurgists vary the relative amounts of copper and zinc in brass to tailor the metal's properties to its intended use—the higher the zinc content relative to the copper content, the more brittle the brass.

Mixtures themselves can be classified according to how uniformly the substances within them mix. In a **heterogeneous mixture**, such as oil and water, the composition varies from one region to another. In a **homogeneous mixture**, such as salt water or sweetened tea, the composition is the same throughout. Homogeneous mixtures have uniform compositions because the atoms or molecules that compose them mix uniformly. Remember that the properties of matter are determined by the atoms or molecules that compose it.

To summarize, as shown in Figure 3.8:

- Matter may be a pure substance, or it may be a mixture.
- A pure substance may be either an element or a compound.
- A mixture may be either homogenous or heterogeneous.
- Mixtures may be composed of two or more elements, two or more compounds, or a combination of both.

EXAMPLE 3.1 Classifying Matter

Classify each of the following as a pure substance or a mixture. If it is a pure substance, classify it as an element or a compound; if it is a mixture, classify it as homogeneous or heterogeneous.

(a) a lead weight
(b) seawater
(c) distilled water
(d) Italian salad dressing

Solution:
Begin by examining the alphabetical listing of pure elements inside the back cover of this text. If the substance appears in that table, it is a pure substance and an element. If it is not in the table but is a pure substance, then it is a compound. If the substance is not a pure substance, then it is a mixture. Use your knowledge about the mixture to determine whether it is homogeneous or heterogeneous.

(a) Lead is listed in the table of elements. It is a pure substance and an element.
(b) Seawater is composed of several substances, including salt and water; it is a mixture. It has a uniform composition, so it is a homogeneous mixture.
(c) Distilled water is not listed in the table of elements, but it is a pure substance (water); therefore, it is a compound.
(d) Italian salad dressing contains a number of substances and is therefore a mixture. It usually separates into at least two distinct regions with different composition and is therefore a heterogeneous mixture.

SKILLBUILDER 3.1 Classifying Matter

Classify each of the following as a pure substance or a mixture. If it is a pure substance, classify it as an element or a compound. If it is a mixture, classify it as homogeneous or heterogeneous.

(a) mercury in a thermometer
(b) exhaled air
(c) minestrone soup
(d) sugar

FOR MORE PRACTICE Example 3.12; Problems 29, 30, 31, 32, 33, 34.

Note: The answers to all Skillbuilders appear at the end of the chapter.

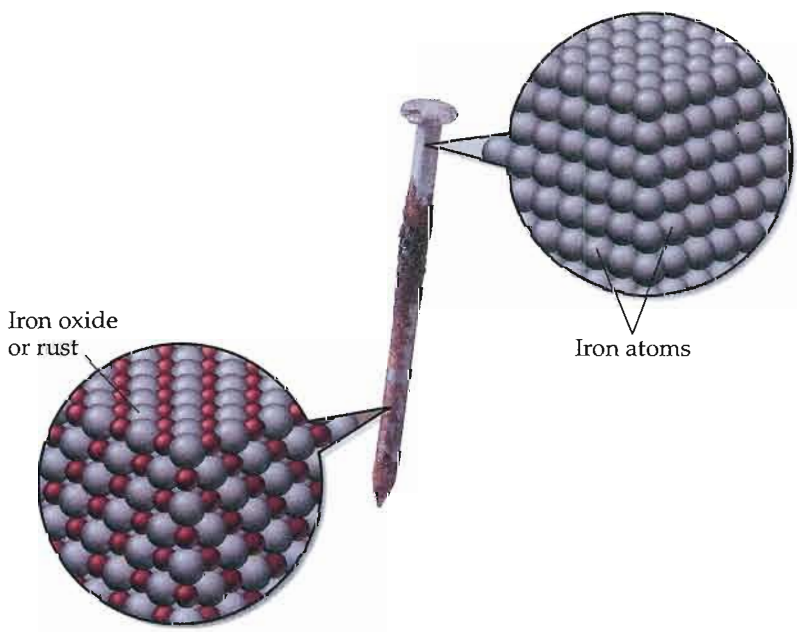
3.5 How We Tell Different Kinds of Matter Apart: Physical and Chemical Properties

In daily life, we distinguish one substance from another based on the substance's properties. For example, we distinguish water from alcohol based on their different smells, or we distinguish gold from silver based on their different colors. The characteristics we use to distinguish one substance from another are called **properties**. Different substances have unique properties that characterize them and distinguish them from other substances.

In chemistry, we differentiate between **physical properties**, those that a substance displays without changing its composition, and **chemical properties**, those that a substance displays only through changing its composition. For example, the characteristic odor of gasoline is a physical property—gasoline does not change its composition when it exhibits its odor. On the other hand, the flammability of gasoline is a chemical property—gasoline does change its composition when it burns.

The atoms or molecules that compose a substance do not change when the substance displays its physical properties. For example, the boiling point of water—a physical property—is 100 °C. When water boils, it changes from a liquid to a gas, but the gas is still water (◀ Figure 3.9). On the other hand, the susceptibility of iron to rust is a chemical property—iron must change into iron oxide to display this property (▼ Figure 3.10). Physical properties include odor, taste, color, appearance, melting point, boiling point, and density. Chemical properties include corrosiveness, flammability, acidity, toxicity, and other chemical characteristics.

▲ **Figure 3.9 A physical property** The boiling point of water is a physical property, and boiling is a physical change. When water boils, it turns into a gas, but the water molecules are the same in both the liquid water and the gaseous steam.



▶ **Figure 3.10 A chemical property** The susceptibility of iron to rusting is a chemical property, and rusting is a chemical change. When iron rusts, it turns from iron to iron oxide.

EXAMPLE 3.2 Physical and Chemical Properties

Determine whether each of the following is a physical or chemical property.

(a) the tendency of copper to turn green when exposed to air
(b) the tendency of automobile paint to dull over time
(c) the tendency of gasoline to evaporate quickly when spilled
(d) the low mass (for a given volume) of aluminum relative to other metals

Solution:

(a) Copper turns green because it reacts with gases in air to form compounds; this is a chemical property.
(b) Automobile paint dulls over time because it can fade (decompose) due to sunlight or it can react with oxygen in air. In either case, this is a chemical property.
(c) Gasoline evaporates quickly because it has a low boiling point; this is a physical property.
(d) Aluminum's low mass (for a given volume) relative to other metals is due to its low density; this is a physical property.

SKILLBUILDER 3.2 Physical and Chemical Properties

Determine whether each of the following is a physical or chemical property.

(a) the explosiveness of hydrogen gas
(b) the bronze color of copper
(c) the shiny appearance of silver
(d) the ability of dry ice to sublime (change from solid directly to vapor)

FOR MORE PRACTICE Example 3.13; Problems 35, 36, 37, 38.

3.6 How Matter Changes: Physical and Chemical Changes

Every day, we witness changes in matter: Ice melts, iron rusts, and fruit ripens, for example. What happens to the atoms and molecules that compose these substances during the change? The answer depends on the kind of change. In a **physical change**, matter changes its appearance but not its composition. For example, when ice melts, it looks different—water looks different from ice—but its composition is the same. Solid ice and liquid water are both composed of water molecules, so melting is a physical change. Similarly, when glass shatters, it looks different, but its composition remains the same—it is still glass. Again, this is a physical change. On the other hand, in a **chemical change**, matter *does* change its composition. For example, copper turns green upon continued exposure to air because it reacts with gases in air to form new compounds. This is a chemical change. Matter undergoes a chemical change when it undergoes a **chemical reaction**. In a chemical reaction, the substances present before the chemical change are called **reactants**, and the substances present after the change are called **products**:

$$\text{Reactants} \xrightarrow[\text{Chemical Change}]{} \text{Products}$$

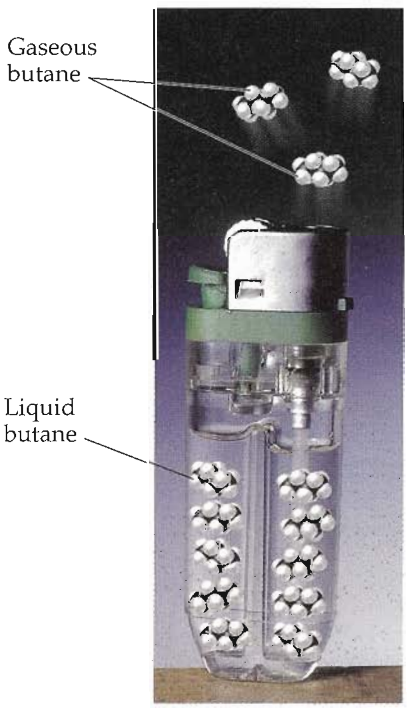
We cover chemical reactions in much more detail in Chapter 7.

Phase changes are transformations from one state of matter (such as solid or liquid) to another.

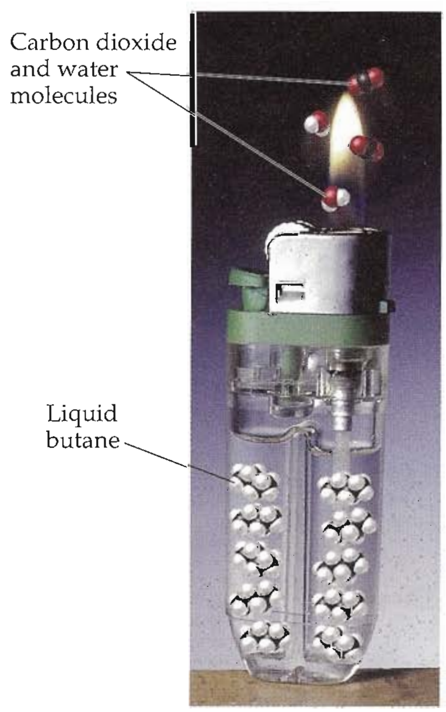
The differences between physical and chemical changes are not always apparent. Only chemical examination of the substances before and after the change can verify whether the change is physical or chemical. For many cases, however, we can identify chemical and physical changes based on what we know about the changes. Phase changes, such as melting or boiling, or changes that involve merely appearance, such as those produced by cutting or crushing, are always physical changes. Changes involving chemical reactions—often evidenced by heat exchange or color changes—are chemical changes.

The main difference between chemical and physical changes is related to the changes at the molecular and atomic level. In physical changes, the atoms that compose the matter *do not* change their fundamental associations, even though the matter may change its appearance. In chemical changes, atoms do change their fundamental associations, resulting in matter with a new identity. *A physical change results in a different form of the same substance, while a chemical change results in a completely new substance.*

Consider physical and chemical changes in liquid butane, the substance used to fuel butane lighters. In many lighters, you can see the liquid butane through the plastic case of the lighter. If you push the fuel button on the lighter without turning the flint, some of the liquid butane vaporizes to gaseous butane—you can usually hear hissing as it leaks out (▼ Figure 3.11). Since the liquid butane and the gaseous butane are both composed of butane molecules, this is a physical change. On the other hand, if you push the button *and* turn the flint to create a spark, a chemical change occurs. The butane molecules react with oxygen molecules in air to form new molecules, carbon dioxide and water (▼ Figure 3.12). The change is chemical because the molecules that compose the butane have changed into different molecules.



▲ **Figure 3.11 Vaporization: a physical change** If you push the button on a lighter without turning the flint, some of the liquid butane vaporizes to gaseous butane. Since the liquid butane and the gaseous butane are both composed of butane molecules, this is a physical change.



▲ **Figure 3.12 Burning: a chemical change** If you push the button *and* turn the flint to create a spark, you produce a flame. The butane molecules react with oxygen molecules in air to form new molecules, carbon dioxide and water. This is a chemical change.

EXAMPLE 3.3 Physical and Chemical Changes

Determine whether each of the following is a physical or chemical change.

(a) the rusting of iron
(b) the evaporation of fingernail-polish remover (acetone) from the skin
(c) the burning of coal
(d) the fading of a carpet upon repeated exposure to sunlight

Solution:

(a) Iron rusts because it reacts with oxygen in air to form iron oxide; therefore, this is a chemical change.
(b) When fingernail-polish remover (acetone) evaporates, it changes from liquid to gas, but it remains acetone; therefore, this is a physical change.
(c) Coal burns because it reacts with oxygen in air to form carbon dioxide; this is a chemical change.
(d) A carpet fades on repeated exposure to sunlight because the molecules that give the carpet its color are decomposed by sunlight; this is a chemical change.

SKILLBUILDER 3.3 Physical and Chemical Changes

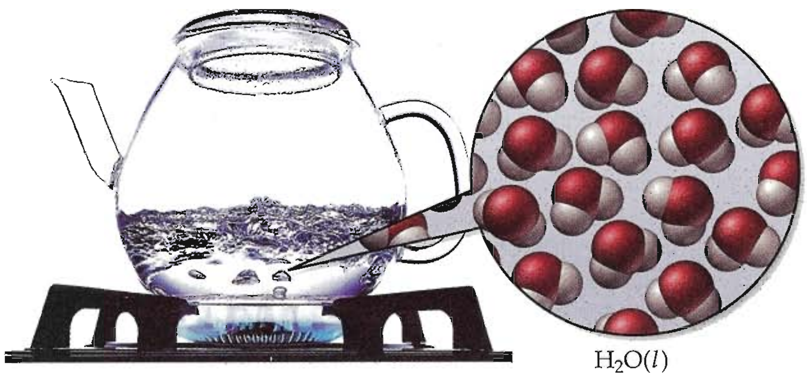
Determine whether each of the following is a physical or chemical change.

(a) copper metal forming a blue solution when it is dropped into colorless nitric acid
(b) a passing train flattening a penny placed on a railroad track
(c) ice melting into liquid water
(d) a match igniting a firework

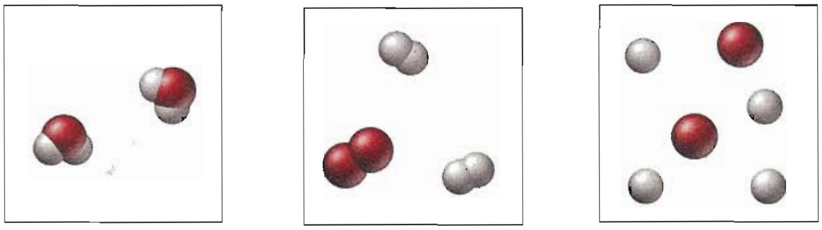
FOR MORE PRACTICE Example 3.14; Problems 39, 40, 41, 42.

CONCEPTUAL CHECKPOINT 3.1

In the figure shown here, liquid water is being vaporized into steam.



Which of the following diagrams best represents the molecules in the steam?

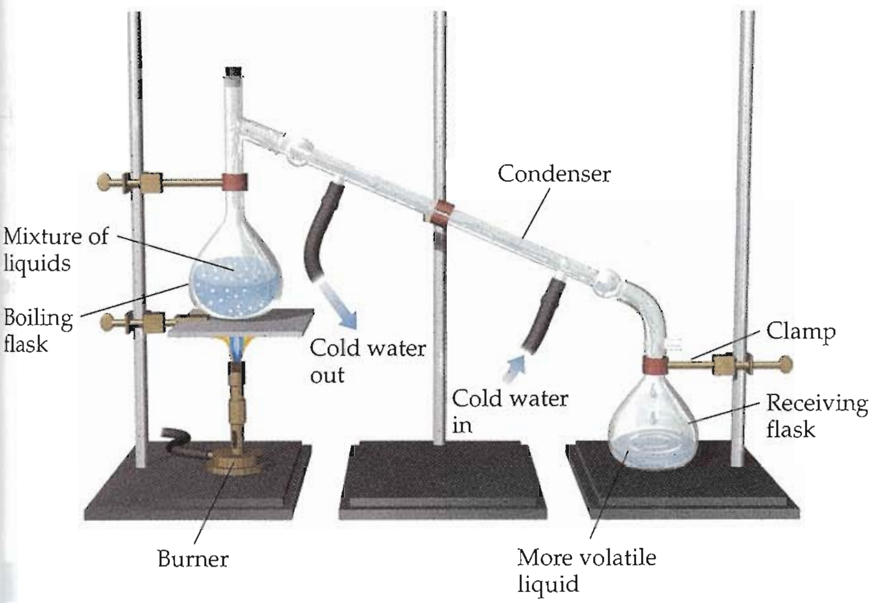


(a) (b) (c)

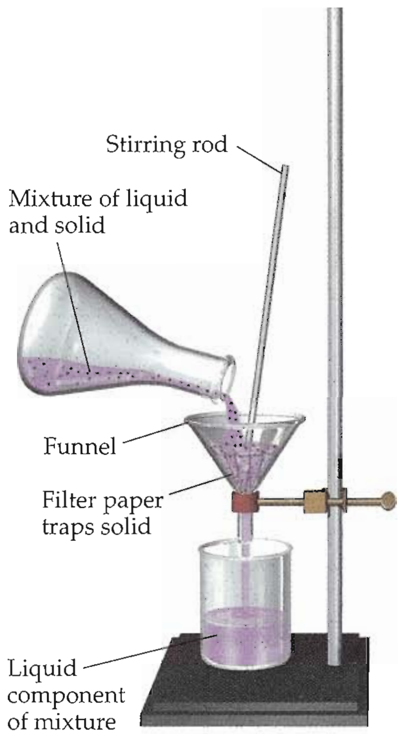
Note: The answers to all Conceptual Checkpoints appear at the end of the chapter.

SEPARATING MIXTURES THROUGH PHYSICAL CHANGES

Chemists often want to separate mixtures into their components. Such separations can be easy or difficult, depending on the components in the mixture. In general, mixtures are separable because the different components have different properties. Various techniques that exploit these differences can be used to achieve separation. For example, oil and water are immiscible (do not mix) and have different densities. For this reason, oil floats on top of water and can be separated from water by **decanting**—carefully pouring off—the oil into another container. Mixtures of miscible liquids can usually be separated by **distillation**, a process in which the mixture is heated to boil off the more **volatile** (easily vaporizable) liquid. The volatile liquid is then recondensed in a condenser and collected in a separate flask (▼ Figure 3.13). If a mixture is composed of a solid and a liquid, the two can be separated by **filtration**, in which the mixture is poured through filter paper usually held in a funnel (▼ Figure 3.14).



▲**Figure 3.13 Separating a mixture of two liquids by distillation** The liquid with the lower boiling point vaporizes first. The vapors are collected and cooled until they condense back into liquid form.



▲**Figure 3.14 Separating a solid from a liquid by filtration**

3.7 Conservation of Mass: There Is No New Matter

As we have seen, our planet, our air, and even our own bodies are composed of matter. Physical and chemical changes do not destroy matter, nor do they create new matter. Recall from Chapter 1 that Antoine Lavoisier, by studying combustion, established the law of conservation of mass, which states:

This law is a slight oversimplification. In nuclear reactions, covered in Chapter 17, significant changes in mass can occur. In chemical reactions, however, the changes are so minute that they can be ignored.

> Matter is neither created nor destroyed in a chemical reaction.

During physical and chemical changes, the total amount of matter remains constant. How does this happen? When we burn butane in a lighter, the butane slowly disappears. Where does it go? It combines with oxygen to form carbon dioxide and water that go into the surrounding air. The mass of the carbon dioxide and water that form, however, must exactly equal the mass of the butane and oxygen that combined.

We examine the quantitative relationships in chemical reactions in Chapter 8.

For example, 58 g of butane will react with 208 g of oxygen to form 176 g of carbon dioxide and 90 g of water.

$$\underbrace{\begin{matrix}\text{Butane} + \text{Oxygen} \\ 58\text{ g} + 208\text{ g}\end{matrix}}_{266\text{ g}} \longrightarrow \underbrace{\begin{matrix}\text{Carbon Dioxide} + \text{Water} \\ 176\text{ g} + 90\text{ g}\end{matrix}}_{266\text{ g}}$$

The sum of the masses of the butane and oxygen, 266 g, is equal to the sum of the masses of the carbon dioxide and water, which is also 266 g. Matter is conserved.

EXAMPLE 3.4 Conservation of Mass

A chemist forms 16.6 g of potassium iodide by combining 3.9 g of potassium with 12.7 g of iodine. Show that these results are consistent with the law of conservation of mass.

Solution:

The sum of the masses of the potassium and iodine is:

$$3.9\text{ g} + 12.7\text{ g} = 16.6\text{ g}$$

The sum of the masses of potassium and iodine equals the mass of the product, potassium iodide. The results are consistent with the law of conservation of mass.

SKILLBUILDER 3.4 Conservation of Mass

Suppose 12 g of natural gas combines with 48 g of oxygen in a flame. The chemical change produces 33 g of carbon dioxide and how many grams of water?

FOR MORE PRACTICE Example 3.15; Problems 43, 44, 45, 46, 47, 48.

CONCEPTUAL CHECKPOINT 3.2

Consider a drop of water that is put into a flask, sealed with a cap, and heated until the droplet vaporizes. Does the mass of the container and water change after heating?