In this chapter we address the question "What exactly is chemistry about?" In addition, we consider common terminology associated with the field of chemistry. Much of this terminology is introduced in the context of the ways in which matter is classified. Like all other sciences, chemistry has its own specific language. It is necessary to restrict the meanings of some words so that all chemists (and those who study chemistry) can understand a given description of a chemical phenomenon in the same way.

### 1.1 Chemistry: The Study of Matter

Chemistry is the field of study concerned with the characteristics, composition, and transformations of matter. What is matter? Matter is anything that has mass and occupies space. The term mass refers to the amount of matter present in a sample.

Matter includes all things—both living and nonliving—that can be seen (such as plants, soil, and rocks) as well as things that cannot be seen (such as air and bacteria). Not considered to be matter are the various forms of energy, such as heat, light, and electricity. However, chemists must be concerned with energy as well as matter, because almost all changes that matter undergoes involve the release or absorption of energy.

The scope of chemistry is extremely broad, and it touches every aspect of our lives. An iron gate rusting, a chocolate cake baking, the diagnosis and treatment of a heart attack, the propulsion of a jet airliner, and the digesting of food all fall within the realm of chemistry (see Figure 1.1). The key to understanding such diverse processes is an understanding...
The term chemistry is derived from the word alchemy, which denotes practices carried out during the Middle Ages in an attempt to transform something common into something precious (in particular, lead into gold). Alchemy originated in Alexandria Egypt, and the term alchemy is derived from the Greek al (“the”) and khemia (a native name for Egypt).

Practice Questions and Problems

1.1 Classify each of the following as matter or energy (nonmatter).

1.2 What three aspects of matter are chemists particularly interested in?

Physical States of Matter

Three physical states exist for matter: solid, liquid, and gas. The classification of a given matter sample in terms of physical state is based on whether its shape and volume are definite or indefinite.

A solid is the physical state characterized by a definite shape and a definite volume. A silver dollar has the same shape and volume whether it is placed in a large container or on a table top (Figure 1.2a). For solids in powdered or granulated forms, such as sugar or salt, a quantity of the solid takes the shape of the portion of the container it occupies, but each individual particle has a definite shape and volume. A liquid is the physical state characterized by an indefinite shape and a definite volume. A liquid always takes the shape of its container to the extent that it fills the container (Figure 1.2b). A gas is the physical state characterized by an indefinite shape and an indefinite volume. A gas always completely fills its container, adopting both its volume and its shape (Figure 1.2c).
The state of matter observed for a particular substance depends on its temperature, the surrounding pressure, and the strength of the forces holding its structural particles together. At the temperatures and pressures normally encountered on Earth, water is one of the few substances found in all three of its physical states: solid ice, liquid water, and gaseous steam (Figure 1.3). Under laboratory conditions, states other than those commonly observed can be attained for almost all substances. Oxygen, which is nearly always thought of as a gas, becomes a liquid at $-183^\circ$C and a solid at $-218^\circ$C. The metal iron is a gas at extremely high temperatures (above 3000°C).

**Practice Questions and Problems**

1.3 Give a characteristic that distinguishes
   a. liquids from solids   b. gases from liquids

1.4 Give a characteristic that is the same for
   a. liquids and solids   b. gases and liquids

1.5 Indicate whether each of the following would take the shape of its container and also have a definite volume.
   a. Copper wire   b. Oxygen gas   c. Granulated sugar   d. Liquid water

**1.3 Properties of Matter**

Various kinds of matter are distinguished from each other by their properties. Properties are the distinguishing characteristics of a substance that are used in its identification and description. Each substance has a unique set of properties that distinguishes it from all other substances. Properties of matter are of two general types: physical and chemical.

A physical property is a characteristic of a substance that can be observed without changing the basic identity of the substance. Common physical properties include color, odor, physical state (solid, liquid, or gas), melting point, boiling point, and hardness.

During the process of determining a physical property, the physical appearance of a substance may change, but the substance’s identity does not. For example, it is impossible to measure the melting point of a solid without changing the solid into a liquid. Although the liquid’s appearance is much different from that of the solid, the substance is still the same; its chemical identity has not changed. Hence melting point is a physical property.
> **Chemical** properties describe the ability of a substance to form new substances, either by reaction with other substances or by decomposition. **Physical** properties are properties associated with a substance’s physical existence. They can be determined without reference to any other substance, and their determination causes no change in the identity of the substance.

**Figure 1.4** The green color of the Statue of Liberty (present before it was restored) results from the reaction of the copper skin of the statue with the components of air. The fact that copper will react with the components of air is a chemical property of copper.

A **chemical property** is a characteristic of a substance that describes the way the substance undergoes or resists change to form a new substance. For example, copper objects turn green when exposed to moist air for long periods of time (Figure 1.4); this is a chemical property of copper. The green coating formed on the copper is a new substance that results from the copper’s reaction with oxygen, carbon dioxide, and water present in air. The properties of this new substance (the green coating) are very different from those of metallic copper. On the other hand, gold objects resist change when exposed to air for long periods of time. The lack of reactivity of gold with air is a chemical property of gold.

Most often the changes associated with chemical properties result from the interaction (reaction) of a substance with one or more other substances. However, the presence of a second substance is not an absolute requirement. Sometimes the presence of energy (usually heat or light) can trigger the change called decomposition. The fact that hydrogen peroxide, in the presence of either heat or light, decomposes into the substances water and oxygen is a chemical property of hydrogen peroxide.

When we specify chemical properties, we usually give conditions such as temperature and pressure because they influence the interactions between substances. For example, the gases oxygen and hydrogen are unreactive toward each other at room temperature, but they interact explosively at a temperature of several hundred degrees.

### Practice Questions and Problems

1.6 Classify each of the following properties of the substance magnesium as a physical property or a chemical property.
   - a. Is a solid at room temperature
   - b. Ignores upon heating in air
   - c. Melts at 651°C
   - d. Does not react with cold water

1.7 Indicate whether each of the following statements describes a physical property or a chemical property.
   - a. Aspirin tablets can be pulverized with a hammer.
   - b. Mercury is a liquid at room temperature.
   - c. Beryllium metal vapor is extremely toxic to humans.
   - d. Nitric acid discolors the skin by reacting with skin protein.

---

### Changes in Matter

Changes in matter are common and familiar occurrences. Changes take place when food is digested, paper is burned, and a pencil is sharpened. Like properties of matter, changes in matter are classified into two categories: physical and chemical.

A **physical change** is a process in which a substance changes its physical appearance but not its chemical composition. A new substance is never formed as a result of a physical change.

A change in physical state is the most common type of physical change. Melting, freezing, evaporation, and condensation are all changes of state. In any of these processes, the composition of the substance undergoing change remains the same even though its physical state and appearance change. The melting of ice does not produce a new substance; the substance is water both before and after the change (see Figure 1.5). Similarly, the steam produced from boiling water is still water.

A **chemical change** is a process in which a substance undergoes a change in chemical composition. Chemical changes always involve conversion of the material or materials under consideration into one or more new substances, each of which has distinctly different properties and composition from the original materials. Consider, for example, the rusting of iron objects left exposed to moist air (Figure 1.6). The reddish brown sub-
stance (the rust) that forms is a new substance with chemical properties that are obviously different from those of the original iron.

Chemists study the nature of changes in matter to learn how to bring about favorable changes and prevent undesirable ones. The control of chemical change has been a major factor in attainment of the modern standard of living now enjoyed by most people in the developed world. The many plastics, synthetic fibers, and prescription drugs now in common use are the result of controlled chemical change.

On the basis of the discussion in this section and the preceding one, some generalizations concerning the use of the terms physical and chemical are in order.

1. Whenever the term physical is used to modify another term, as in physical property or physical change, it always conveys the idea that the composition (chemical identity) of the substance involved did not change.

2. Whenever the term chemical is used to modify another term, as in chemical property or chemical change, it always conveys the idea that the composition (chemical identity) of the substance(s) involved either did change or successfully resisted change as the result of an external challenge to its identity.

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**Example 1.1 Correct Use of the Terms Physical and Chemical**

Correctly complete each of the following sentences by placing the word physical or chemical in the blank.

a. The fact that pure aspirin melts at 143°C is a ___ property of aspirin.
   Solution: Physical.

b. The fact that potassium metal vigorously interacts with water to produce hydrogen gas is a ___ property of potassium.
   Solution: Chemical.

c. Straightening a bent piece of iron with a hammer is an example of a ___ change.
   Solution: Physical.

d. The ignition of a match is an example of a ___ change.
   Solution: Chemical.

---

**Practice Questions and Problems**

### 1.8

Indicate whether each of the following statements describes a physical change or a chemical change.

a. An Alka-Seltzer tablet is dropped into water.
   Solution: Chemical.

b. A table leg is fashioned from a piece of wood.
   Solution: Physical.

c. Water placed in the refrigerator is converted into ice cubes.
   Solution: Physical.

d. Leaves turn red in the autumn.
   Solution: Physical.

### 1.9

Correctly complete each of the following sentences by placing the word physical or chemical in the blank.

a. The destruction of a newspaper through burning involves a ___ change.
   Solution: Chemical.

b. The grating of a piece of cheese is a ___ change.
   Solution: Physical.

c. The heating of a blue powdered material to produce a white glassy substance and a gas is a ___ change.
   Solution: Chemical.

d. The crushing of some ice to make some ice chips is a ___ change.
   Solution: Physical.
1.5 Pure Substances and Mixtures

In addition to its classification by physical state (Section 1.2), matter can also be classified in terms of its chemical composition as a pure substance or as a mixture. A pure substance is a single kind of matter that cannot be separated into other kinds of matter by any physical means. All samples of a pure substance contain only that substance and nothing else. Pure water is water and nothing else. Pure sucrose (table sugar) contains only that substance and nothing else.

A pure substance always has a definite and constant composition. This invariant composition dictates that the properties of a pure substance are always the same under a given set of conditions. Collectively, these definite and constant physical and chemical properties constitute the means by which we identify the pure substance.

A mixture is a physical combination of two or more pure substances in which each substance retains its own chemical identity. Components of a mixture retain their identity because they are physically mixed rather than chemically combined. Consider a mixture of small rock salt crystals and ordinary sand. Mixing these two substances changes neither the salt nor the sand in any way. The larger, colorless salt particles are easily distinguished from the smaller, light-gray sand granules.

One characteristic of any mixture is that its components can be separated by using physical means. In our salt–sand mixture, the larger salt crystals could be—though very tediously—"picked out" from the sand. A somewhat easier separation method would be to dissolve the salt in water, which would leave the undissolved sand behind. The salt could then be recovered by evaporation of the water. Figure 1.7 shows a heterogeneous mixture of potassium dichromate (orange crystals) and iron filings. A magnet can be used to separate the components of this mixture.

Another characteristic of a mixture is variable composition. Numerous different salt–sand mixtures, with compositions ranging from a slightly salty sand mixture to a slightly sandy salt mixture, could be made by varying the amounts of the two components.

Mixtures are subclassified as heterogeneous or homogeneous. This subclassification is based on visual recognition of the mixture's components. A heterogeneous mixture contains visibly different phases (parts), each of which has different properties. A nonuniform appearance is a characteristic of all heterogeneous mixtures. Examples include chocolate chip cookies and blueberry muffins. Naturally occurring heterogeneous mixtures include rocks, soils, and wood.

A homogeneous mixture contains only one visibly distinct phase (part), which has uniform properties throughout. The components present in a homogeneous mixture can-

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**Figure 1.7** (a) A magnet (on the left) and a mixture consisting of potassium dichromate (the orange crystals) and iron filings. (b) The magnet can be used to separate the iron filings from the potassium dichromate.
not be visually distinguished. A sugar–water mixture in which all of the sugar has dissolved has an appearance similar to that of pure water. Air is a homogeneous mixture of gases; motor oil and gasoline are multicomponent homogeneous mixtures of liquids; and metal alloys such as 14-karat gold (a mixture of copper and gold) are examples of homogeneous mixtures of solids.

Figure 1.8 summarizes what we have learned thus far about various classifications of matter.

**Practice Questions and Problems**

1.10 Classify each of the following statements as true or false.
   a. All heterogeneous mixtures must contain three or more substances.
   b. Pure substances cannot have a variable composition.
   c. Substances maintain their identity in a heterogeneous mixture but not in a homogeneous mixture.
   d. A homogeneous mixture contains only one visibly distinct phase.

1.11 Assign each of the following descriptions of matter to one of these categories: heterogeneous mixture, homogeneous mixture, or pure substance.
   a. Two substances present, two phases present
   b. Two substances present, one phase present
   c. One substance present, one phase present
   d. Three substances present, three phases present

1.12 Classify each of the following samples of matter as a heterogeneous mixture, homogeneous mixture, or pure substance.
   a. Water and dissolved salt
   b. Water and sand
   c. Water, ice, and oil
   d. Salt water and sugar water

---

**1.6 Elements and Compounds**

Chemists have isolated and characterized an estimated 8.5 million pure substances. A very small number of these pure substances, 113 to be exact, are different from all of the others. They are elements. All of the rest, the remaining millions, are compounds. What distinguishes an element from a compound?
Both elements and compounds are pure substances.

The definition for the term element that is given here will do for now. After considering the concept of atomic number (Section 3.2), we will give a more precise definition.

Every known compound is made up of some combination of the 113 known elements. In any given compound, the elements are combined chemically in fixed proportions by mass.

There are three major property distinctions between compounds and mixtures.
1. Compounds have properties distinctly different from those of the substances that combined to form the compound. The components of mixtures retain their individual properties.
2. Compounds have a definite composition. Mixtures have a variable composition.
3. Physical methods are sufficient to separate the components of a mixture. The components of a compound cannot be separated by physical methods; chemical methods are required.

Figure 1.9 A pure substance can be either an element or a compound.

An element is a pure substance that cannot be broken down into simpler pure substances by ordinary chemical means such as a reaction, an electric current, heat, or a beam of light. The metals gold, silver, and copper are all elements.

A compound is a pure substance that can be broken down into two or more simpler pure substances by chemical means. Water is a compound. By means of an electric current, water can be broken down into the gases hydrogen and oxygen, both of which are elements. The ultimate breakdown products for any compound are elements. A compound’s properties are always different from those of its component elements, because the elements are chemically rather than physically combined in the compound (Figure 1.9).

Even though two or more elements are obtained from decomposition of compounds, compounds are not mixtures. Why is this so? Remember, substances can be combined either physically or chemically. Physical combination of substances produces a mixture. Chemical combination of substances produces a compound, a substance in which combining entities are bound together. No such binding occurs during physical combination.

The following Chemistry at a Glance summarizes what we have learned thus far about matter, including pure substances, elements, compounds, and mixtures.

Practice Questions and Problems

1.3 Indicate whether each of the following statements is true or false.
   a. Both elements and compounds are pure substances.
   b. A compound results from the physical combination of two or more elements.
   c. Compounds, but not elements, can have a variable composition.
   d. A compound must contain at least two elements.

1.4 On the basis of the information given, classify each of the pure substances A through D as elements or compounds, or indicate that no such classification is possible because of insufficient information.
   a. Substance A cannot be broken down into simpler substances by chemical means.
   b. Substance B decomposes upon heating.
   c. Heating substance C to 1000°C causes no change in it.
   d. Substance D readily reacts with the element chlorine.
1.15 From the information given in the following equations, classify each of the substances A through F as elements or compounds, or indicate that no such classification is possible because of insufficient information.

a. \( A + B \rightarrow C \)

b. \( D \rightarrow E + F \)

1.7 Discovery and Abundance of the Elements

The discovery and isolation of the 113 known elements, the building blocks for all matter, have taken place over a period of several centuries. Most of the discoveries have occurred since 1700, the 1800s being the most active period.

Eighty-eight of the 113 elements occur naturally, and 25 have been synthesized in the laboratory by bombarding samples of naturally occurring elements with small particles. Figure 1.10 shows samples of selected naturally occurring elements. The synthetic
A student who attended a university in the year 1700 would have been taught that 13 elements existed. In 1750 he or she would have learned about 16 elements, in 1800 about 34, in 1850 about 59, in 1900 about 82, and in 1950 about 98. Today's total of 113 elements was reached in 1999.

Any increase in the number of known elements from 113 will result from the production of additional synthetic elements. Current chemical theory strongly suggests that all naturally occurring elements have been identified. The isolation of the last of the known naturally occurring elements, rhenium, occurred in 1925.

(laboratory-produced) elements are all unstable (radioactive) and usually revert quickly to the naturally occurring elements.

The naturally occurring elements are not evenly distributed on Earth and in the universe. What is startling is the nonuniformity of the distribution. A small number of elements account for the majority of elemental particles (atoms). (An atom is the smallest particle of an element that can exist. See Section 1.9.)

Studies of the radiation emitted by stars enable scientists to estimate the elemental composition of the universe (Figure 1.11a). Results indicate that two elements, hydrogen and helium, are absolutely dominant. All other elements are mere “impurities” when their abundances are compared with those of these two dominant elements. In this big picture, in which Earth is but a tiny microdot, 91% of all elemental particles (atoms) are hydrogen, and almost all of the remaining 9% are helium.

Figure 1.11 Abundance of elements in the universe and in Earth’s crust (in atom percent).
If we narrow our view to the chemical world of humans—Earth’s crust (its waters, atmosphere, and outer solid surface)—a different perspective emerges. Again, two elements dominate, but this time they are oxygen and silicon. Figure 1.11b provides information on elemental abundances for Earth’s crust. The numbers given are atom percents—that is, the percentage of total atoms that are of a given type. Note that the eight elements listed (the only elements with atom percents greater than 1%) account for over 98% of total atoms in Earth’s crust. Note also the dominance of oxygen and silicon; these two elements account for 80% of the atoms that make up the chemical world of humans.

The elements of Earth’s crust are not distributed equally throughout it. Ore deposits of some elements are found only in localized regions of the crust. Thus not all countries have domestic access to all elements. Even the United States, with its wealth of natural resources, lacks domestic sources of certain elements. For example, the United States has no domestic production sources for the elements nickel, chromium, and cobalt. All new supplies of these elements must be imported from other countries.

To some observers, our nation’s reliance on such imports constitutes a dangerous dependence, portending a “strategic materials crisis” equal in seriousness to the “energy crisis” associated with the importation of crude oil and petroleum products. Others see the U.S. position as manageable, though not without dangers and difficulties. All observers agree that if supplies of such imported elements were cut off, many readjustments would be made in lifestyles in the United States.

Chemical Portraits 1 profiles the “imported” elements nickel, chromium, and cobalt. The major use for all three of these elements is in metal alloys. (Alloys are solid-state homogeneous mixtures; see Section 1.5.) Import dependence for each of these elements is 60% or greater. (Import dependence is not 100% because significant supplies of these elements are now obtained from domestic recycling of scrap materials, such as spent metal alloys, that contain these elements.

### Strategic Elements—Dependence on Imports

#### Nickel (Ni)
**Profile:** The United States imports 55–65% of its nickel, of which 39% comes from Canada, 15% comes from Norway, and 13% comes from Russia.

**Uses:** Nickel’s primary use is in stainless steel, a type of steel that is corrosion resistant. Adding nickel to steel increases its workability and strength at high temperatures. Some nickel is used in making coins; a U.S. nickel (5 cents) contains 25% nickel and 75% copper. Although nickel is relatively scarce in the Earth’s crust, it is believed that large deposits of this element exist within the Earth’s core.

What is the importance of the domestic recycling of scrap metals containing nickel?

#### Chromium (Cr)
**Profile:** The United States imports 75–80% of its chromium, of which 46% comes from South Africa, 14% comes from Kazakhstan, and 10% comes from Russia.

**Uses:** Chromium’s primary use is as an ingredient in stainless steel; it is the chromium present that gives such steel its corrosion resistance. Chromium atoms near the surface of the steel react with the oxygen of air to produce a chromium-oxygen compound. This compound forms a corrosion-resistant protective coating on the surface of the steel.

What properties of chromium are responsible for the practice of chrome-plating other metal objects?

#### Cobalt (Co)
**Profile:** The United States imports 73–76% of its cobalt, of which 23% comes from Norway, 20% comes from Finland, and 13% comes from Zambia.

**Uses:** Cobalt’s primary use is as an ingredient in superalloys (alloys that can withstand higher temperatures than stainless steel can). Such superalloys are used primarily in aircraft gas turbine engines. Cobalt, like iron, has magnetic properties and it retains them at temperatures far higher than does iron. This leads to cobalt’s use in small, powerful magnets for electrical equipment.

What role does the element cobalt play in human nutrition?

See the text web site at [http://chemistry.college.hmco.com/students](http://chemistry.college.hmco.com/students) for answers to the above questions and for further information.
Table 1.1
Abundance of Elements in the Human Body (in atom percent)

<table>
<thead>
<tr>
<th>Element</th>
<th>Percent of total number of atoms in the human body</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrogen</td>
<td>63</td>
</tr>
<tr>
<td>oxygen</td>
<td>25.5</td>
</tr>
<tr>
<td>carbon</td>
<td>9.5</td>
</tr>
<tr>
<td>nitrogen</td>
<td>1.4</td>
</tr>
<tr>
<td>calcium</td>
<td>0.31</td>
</tr>
<tr>
<td>phosphorus</td>
<td>0.22</td>
</tr>
<tr>
<td>potassium</td>
<td>0.06</td>
</tr>
<tr>
<td>sulfur</td>
<td>0.05</td>
</tr>
<tr>
<td>chlorine</td>
<td>0.03</td>
</tr>
<tr>
<td>sodium</td>
<td>0.03</td>
</tr>
<tr>
<td>magnesium</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The distribution of elements in the human body and other living systems is very different from that found in Earth's crust. This distribution is the result of living systems selectively taking up matter from their external environment, rather than simply accumulating matter representative of their surroundings.

Eleven elements are found in the human body in atom percent levels of 0.01 or greater, as shown in Table 1.1. The high abundances of hydrogen and oxygen in the body reflect its high water content. Hydrogen is over twice as abundant as oxygen, largely because water contains hydrogen and oxygen in a 2-to-1 atom ratio.

Practice Questions and Problems

1.16 Indicate whether each of the following statements about the known elements is true or false.
   a. The majority of the known elements have been discovered since 1900.
   b. At present, 108 elements are known.
   c. Elements that do not occur in nature can be produced in a laboratory setting.
   d. New elements have been identified within the last 10 years.

1.17 Indicate whether each of the following statements about elemental abundances is true or false.
   a. Silicon is the second most abundant element in Earth's crust.
   b. Oxygen is the most abundant element both in Earth's crust and in the human body.
   c. Hydrogen is the most abundant element in the universe but not in Earth's crust.
   d. Two elements account for over three-fourths of the atoms in Earth's crust.

Names and Chemical Symbols of the Elements

Each element has a unique name that, in most cases, was selected by its discoverer. Abbreviations called chemical symbols also exist for the names of the elements. A chemical symbol is a one- or two-letter designation for an element derived from the name of the element. These symbols are used more frequently than the elements' names. They can be written more quickly than the names, and they occupy less space. A complete list of the known elements and their chemical symbols is given in Table 1.2. The chemical symbols and names of the more frequently encountered elements are shown in color in this table.

Note that the first letter of a chemical symbol is always capitalized and that the second is not. Two-letter symbols are often, but not always, the first two letters of the element's name.

Eleven elements have symbols that bear no relationship to the element's English-language name. In ten of these cases, the symbol is derived from the Latin name of the...
Table 1.2
The Chemical Symbols for the Elements*

The symbols and names of the more frequently encountered elements are shown in red.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Symbol</th>
<th>Name</th>
<th>Symbol</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ac</td>
<td>actinium</td>
<td>Ge</td>
<td>germanium</td>
<td>Pr</td>
<td>praseodymium</td>
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<td>hydrogen</td>
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<td>hassium</td>
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<td>iodine</td>
<td>Rh</td>
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<td>In</td>
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<td>Rn</td>
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<td>lutetium</td>
<td>Sg</td>
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*Only 109 elements are listed in this table. Elements 110–112 and 114 discovered (synthesized) in the period 1994–1999, are yet to be named.

*These elements have symbols that were derived from non-English names.

element; in the case of the element tungsten, a German name is the symbol's source. Most of these elements have been known for hundreds of years and date back to the time when Latin was the language of scientists. Elements whose symbols are derived from non-English names are marked with an asterisk in Table 1.2.

Practice Questions and Problems

1.18 In which of the following sequences of elements do all of the elements have two-letter chemical symbols?

a. Magnesium, nitrogen, phosphorus
b. Bromine, iron, calcium
c. Aluminum, copper, chlorine
d. Boron, barium, beryllium
1.9 In which of the following sequences of elements do all of the elements have chemical symbols that start with a letter that is not the first letter of the element’s English name?

a. Silver, gold, mercury
b. Copper, helium, neon
c. Cobalt, chromium, sodium
d. Potassium, iron, lead

1.9 Atoms and Molecules

Consider the process of subdividing a sample of the element gold (or any other element) into smaller and smaller pieces. It seems reasonable that eventually a “smallest possible piece” of gold would be reached that could not be divided further and still be the element gold. This smallest possible unit of gold is called a gold atom. An atom is the smallest particle of an element that can exist and still have the properties of the element.

A sample of any element is composed of atoms of a single type, those of that element. In contrast, a compound must have two or more types of atoms present, because by definition at least two elements must be present (Section 1.6).

No one ever has seen or ever will see an atom with the naked eye; they are simply too small for such observation. However, sophisticated electron microscopes, with magnification factors in the millions, have made it possible to photograph “images” of individual atoms (Figure 1.12).

Atoms are incredibly small particles. Atomic dimensions, although not directly measurable, can be calculated from measurements made on large-size samples of elements. The diameter of an atom is approximately four-billionths of an inch. If atoms of such diameter were arranged in a straight line, it would take 254 million of them to extend a distance of 1 inch (see Figure 1.13).

Free atoms are rarely encountered in nature. Instead, under normal conditions of temperature and pressure, atoms are nearly always found together in aggregates or clusters ranging in size from two atoms to numbers too large to count. When the group or cluster of atoms is relatively small and bound together tightly, the resulting entity is called a molecule. A molecule is a group of two or more atoms that functions as a unit because the atoms are tightly bound together. This resultant “package” of atoms behaves in many ways as a single, distinct particle would.

Figure 1.12 A computer reconstruction of the surface of a sample of a solid as observed with a scanning tunneling microscope. The image reveals the regular pattern of individual atoms. The color was added to the image by computer.
A diatomic molecule is a molecule that contains two atoms. It is the simplest type of molecule that can exist. Next in complexity are triatomic molecules. A triatomic molecule is a molecule that contains three atoms. The molecule present in water, the most common of all compounds, is triatomic; it contains two hydrogen atoms and one oxygen atom. Continuing on numerically, we have tetratomic molecules, pentatomic molecules, and so on.

The atoms contained in a molecule may all be of the same kind, or two or more kinds may be present. In accordance with this observation, molecules are classified into the two categories of homoatomic and heteroatomic. A homoatomic molecule is a molecule in which all atoms present are of the same kind. A substance containing homoatomic molecules must be an element. A heteroatomic molecule is a molecule in which two or more kinds of atoms are present. Substances that contain heteroatomic molecules must be compounds, because the presence of two or more kinds of atoms reflects the presence of two or more kinds of elements.

The fact that homoatomic molecules exist indicates that individual atoms are not always the preferred structural unit for an element. Nearly all of the oxygen present in air is in the form of diatomic molecules. Several other elements, including nitrogen (the other major constituent of air) and hydrogen, are also diatomic in the gaseous state. Chemical Portraits 2 profiles the “diatomic” elements oxygen, nitrogen, and hydrogen. The diatomic nature of these elements can be specified by using the notations $\text{O}_2$, $\text{N}_2$, and $\text{H}_2$ to represent molecules of these elements.

Figure 1.14 shows general models for four simple types of heteroatomic molecules. Comparison of parts (c) and (d) of this figure shows that molecules with the same number of atoms need not have the same arrangement of atoms.

### Chemical Portraits 2

#### Three Well-Known Gaseous Diatomic Elements

**Oxygen ($\text{O}_2$)**

**Profile:** Oxygen, the second most abundant gas in air, constitutes 21% by volume of clean, dry air. This colorless, odorless, tasteless gas is often referred to as the “life-giving” element because a person can live weeks without food, days without water, but only minutes without oxygen. To commercially obtain pure oxygen, air is liquefied at low temperatures, and its various components are separated according to their different boiling points.

**Uses:** The steel industry is the dominant outlet for industrial $\text{O}_2$. Here, impurities are removed from the steel by their reaction with $\text{O}_2$. Medical and life-support uses for oxygen consume less than 2% of commercial oxygen production.

**What is the major use for liquid oxygen in the United States’s space program?**

**Nitrogen ($\text{N}_2$)**

**Profile:** Nitrogen, the most abundant gas in air, constitutes 78% by volume of clean, dry air. Like $\text{O}_2$, it is colorless, odorless, and tasteless, and it is obtained in the pure state through low-temperature extraction from liquid air. Unlike $\text{O}_2$, however, $\text{N}_2$ is a very unreactive gas.

**Uses:** The major industrial use for $\text{N}_2$ gas is as the nitrogen source for making nitrogen-containing fertilizers such as liquid ammonia and ammonium nitrate. Nitrogen is a nutrient required by all plants and plants cannot obtain it from air. Because of its unreactivity, another major use for $\text{N}_2$ is that of a “blanketing agent.” Here it is used to protect substances that would react with $\text{O}_2$ or moisture in air.

**When was nitrogen discovered and by whom?**

**Hydrogen ($\text{H}_2$)**

**Profile:** Hydrogen, unlike $\text{N}_2$ and $\text{O}_2$, is not a constituent of air. Hydrogen molecules are the least massive of all molecules. Because of their small mass, gaseous $\text{H}_2$ molecules are able to acquire velocities sufficient for them to overcome the gravitational forces of the earth and escape to outer space; thus no $\text{H}_2$ is present in the atmosphere. Like $\text{O}_2$ and $\text{N}_2$, $\text{H}_2$ gas is colorless, odorless, and tasteless; like $\text{O}_2$, $\text{H}_2$ molecules are relatively reactive.

**Uses:** About 40% of commercial $\text{H}_2$ production is used to make ammonia, the starting material for nitrogen-fertilizer production. Decomposition of hydrogen-containing compounds such as water and methane is the source of such hydrogen.

**What is the state of development for hydrogen-powered cars?**

*See the text website at [http://chemistry.college.hmco.com/students](http://chemistry.college.hmco.com/students) for answers to the above questions and for further information.*
Figure 1.14 Depictions of various simple heteroatomic molecules using models. Spheres of different sizes and colors represent different kinds of atoms.

(a) A diatomic molecule containing one atom of A and one atom of B

(b) A triatomic molecule containing two atoms of A and one atom of B

(c) A tetrameric molecule containing two atoms of A and two atoms of B

(d) A tetrameric molecule containing three atoms of A and one atom of B

Example 1.2 Classifying Molecules Based on Numbers of and Types of Atoms

Classify each of the following molecules as diatomic, triatomic, etc., and also as homon-atomic or heteroatomic.

(a) Tetrameric and heteroatomic (four atoms; two kinds of atoms)
(b) Triatomic and heteroatomic (three atoms; two kinds of atoms)
(c) Hexatomic and homon-atomic (six atoms; only one kind of atom)
(d) Diatomic and heteroatomic (two atoms; two kinds of atoms)

Solution

A molecule is the smallest particle of a compound capable of a stable independent existence. Continued subdivision of a quantity of table sugar to yield smaller and smaller amounts would ultimately lead to the isolation of one single "unit" of table sugar: a molecule of table sugar. This table sugar molecule could not be broken down any further and still exhibit the physical and chemical properties of table sugar. The table sugar molecule could be broken down further by chemical (not physical) means to produce atoms, but if that occurred, we would no longer have table sugar. The molecule is the limit of physical subdivision. The atom is the limit of chemical subdivision.

Practice Questions and Problems

1.20 Indicate whether each of the following statements is true or false.
(a) Triatomic molecules must contain at least two kinds of atoms.
(b) A molecule of a compound must be heteroatomic.
(c) Heteroatomic molecules do not maintain the properties of their constituent elements.
(d) A molecule of an element may be homon-atomic or heteroatomic, depending on which element is involved.
1.21 Which of the terms *heteroatomic*, *homoatomic*, *diatomic*, *triatomic*, *element*, and *compound* apply to each of the following molecules? (More than one term applies in each situation.)

- a. \( \text{O} - \text{X} \)
- b. \( \text{O} _{\text{Z}} - \text{X} \)
- c. \( \text{X} - \text{X} \)
- d. \( \text{X} - \text{Q} - \text{X} \)

### 1.10 Chemical Formulas

Information about compound composition can be presented in a concise way by using a chemical formula. A **chemical formula** is a notation made up of the symbols of the elements present in a compound and numerical subscripts (located to the right of each symbol) that indicate the number of atoms of each element present in a molecule of the compound.

The chemical formula for the compound aspirin is \( \text{C}_9\text{H}_8\text{O}_4 \). This chemical formula conveys the information that an aspirin molecule contains three different elements—carbon (C), hydrogen (H), and oxygen (O)—and 21 atoms—9 carbon atoms, 8 hydrogen atoms, and 4 oxygen atoms.

When only one atom of a particular element is present in a molecule of a compound, that element’s symbol is written without a numerical subscript in the formula for the compound. The formula for rubbing alcohol, \( \text{C}_2\text{H}_5\text{O} \), reflects this practice for the element oxygen.

In order to write formulas correctly, one must follow the capitalization rules for elemental symbols (Section 1.8). Making the error of capitalizing the second letter of an element’s symbol can dramatically alter the meaning of a chemical formula. The formulas \( \text{CoCl}_2 \) and \( \text{CoCl}_3 \) illustrate this point; the symbol Co stands for the element cobalt, whereas CO stands for one atom of carbon and one atom of oxygen.

Sometimes chemical formulas contain parentheses; an example is \( \text{Al}_2(\text{SO}_4)_3 \). The interpretation of this formula is straightforward; in a formula unit, there are present 2 aluminum (Al) atoms and 3 \( \text{SO}_4 \) groups. The subscript following the parentheses always indicates the number of units in the formula of the polyatomic entity inside the parentheses. In terms of atoms, the formula \( \text{Al}_2(\text{SO}_4)_3 \) denotes 2 aluminum (Al) atoms, \( 3 \times 1 = 3 \) sulfur (S) atoms, and \( 3 \times 4 = 12 \) oxygen (O) atoms. Example 1.3 contains further comments about chemical formulas that contain parentheses.

### Example 1.3 Interpreting Chemical Formulas

For each of the following chemical formulas, state how many atoms of each element are present in one molecule of the substance.

- a. \( \text{HCN} \)—hydrogen cyanide, a poisonous gas
- b. \( \text{C}_18\text{H}_21\text{NO}_3 \)—codeine, a pain-killing drug
- c. \( \text{Ca}_10(\text{PO}_4)_6(\text{OH})_2 \)—hydroxyapatite, present in tooth enamel

#### Solution

- a. One atom each of the elements hydrogen, carbon, and nitrogen is present. Remember that the subscript 1 is implied when no subscript is written.
- b. This formula indicates that 18 carbon atoms, 21 hydrogen atoms, 1 nitrogen atom, and 3 oxygen atoms are present in one molecule of the compound.
- c. There are 10 calcium atoms. The amounts of phosphorus, hydrogen, and oxygen are affected by the subscripts outside the parentheses. There are 6 phosphorus atoms and 2 hydrogen atoms present. Oxygen atoms are present in two locations in the formula. There are a total of 26 oxygen atoms: 24 from the \( \text{PO}_4 \) subunits (\( 6 \times 4 \)) and 2 from the \( \text{OH} \) subunits (\( 2 \times 1 \)).
Practice Questions and Problems

1.22 On the basis of its formula, classify each of the following substances as an element or a compound.
   a. LiCO₃  
   b. CO  
   c. Co  
   d. O₃  
   e. CoCl₂  
   f. COCl₂

1.23 Determine the number of elements and the number of atoms present in molecules represented by the following formulas.
   a. H₂CO₃  
   b. NH₄ClO₄  
   c. CaSO₄  
   d. C₆H₁₀  
   e. Be(CN)₂  
   f. Cu(NO₃)₂

1.24 Write a chemical formula for each of the following substances using the information given for the substance.
   b. A molecule of vitamin C contains 6 atoms of carbon, 8 atoms of hydrogen, and 6 atoms of oxygen.

1.25 What is the chemical formula for each of the following molecules?
   a. X⁻Q⁻  
   b. X⁻Q⁻Q⁻  
   c. Q⁻Q⁻  
   d. X⁻X⁻Q⁻

CONCEPTS TO REMEMBER

Chemistry. Chemistry is the field of study that is concerned with the characterization, composition, and transformations of matter.

Matter. Matter, the substances of the physical universe, is anything that has mass and occupies space. Matter exists in three physical states: solid, liquid, and gas.

Properties of matter. Properties, the distinguishing characteristics of a substance that are used in its identification and description, are of two types: physical and chemical. Physical properties are properties that we can observe without changing a substance into another substance. Chemical properties are properties that matter exhibits as it undergoes or resists changes in chemical composition. The failure of a substance to undergo change in the presence of another substance is considered a chemical property.

Changes in matter. Changes that can occur in matter are classified into two types: physical and chemical. A physical change is a process that does not alter the basic nature (chemical composition) of the substance under consideration. No new substances are ever formed as a result of a physical change. A chemical change is a process that involves a change in the basic nature (chemical composition) of the substance. Such changes always involve conversion of the material or materials under consideration into one or more new substances that have properties and composition distinctly different from those of the original materials.

Pure substances and mixtures. All specimens of matter are either pure substances or mixtures. A pure substance is a form of matter that always has a definite and constant composition. A mixture is a physical combination of two or more pure substances in which the pure substances retain their identity.

Types of mixtures. Mixtures can be classified as heterogeneous or homogeneous on the basis of the visual recognizability of the components present. A heterogeneous mixture contains visibly different parts or phases, each of which has different properties. A homogeneous mixture contains only one phase, which has uniform properties throughout it.

Types of pure substances. A pure substance can be classified as either an element or a compound on the basis of whether it can be broken down into two or more simpler substances by ordinary chemical means. Elements cannot be broken down into simpler substances. Compounds yield two or more simpler substances when broken down. There are 113 pure substances that qualify as elements. There are millions of compounds.

Atoms and molecules. An atom is the smallest particle of an element that can exist and still have the properties of the element. Free isolated atoms are rarely encountered in nature. Instead, atoms are almost always found together in aggregates or clusters. A molecule is a group of two or more atoms that functions as a unit because the atoms are tightly bound together.

Types of molecules. Molecules are of two types: homatomic and heteratomic. Homatomic molecules are molecules in which all atoms present are of the same kind. A pure substance containing homatomic molecules is an element. Heteratomic molecules are molecules in which two or more different kinds of atoms are present. Pure substances that contain heteratomic molecules must be compounds.

Chemical symbols. Chemical symbols are a shorthand notation for the names of the elements. Most consist of two letters; a few involve a single letter. The first letter of a chemical symbol is always capitalized, and the second letter is always lower-case.

Chemical formulas. Chemical formulas are used to specify compound composition in a concise manner. They consist of the symbols of the elements present in the compound and numerical subscripts (located to the right of each symbol) that indicate the number of atoms of each element present in a molecule of the compound.
KEY TERMS

Atom (1.9)  Element (1.6)  Mixture (1.5)
Chemical change (1.4)  Gas (1.2)  Molecule (1.9)
Chemical formula (1.10)  Heteroatomic molecule (1.9)  Physical change (1.4)
Chemical property (1.3)  Heterogeneous mixture (1.5)  Physical property (1.3)
Chemical symbol (1.8)  Homoeoatomic molecule (1.9)  Properties (1.3)
Chemistry (1.1)  Homogeneous mixture (1.5)  Pure substance (1.5)
Compound (1.6)  Liquid (1.2)  Solid (1.2)
Diatomic molecule (1.9)  Matter (1.1)  Triatomic molecule (1.9)

ADDITIONAL PROBLEMS

1.26 Assign each of the following descriptions of matter to one of the following categories: element, compound, or mixture.
   a. One substance present, one phase present, substance cannot be decomposed by chemical means
   b. One substance present, three phases present
   c. Two substances present, two phases present
   d. Two elements present, composition is definite and constant

1.27 Assign each of the following descriptions of matter to one of the following categories: element, compound, or mixture.
   a. One substance present, one phase present, one kind of homoeoatomic molecule present
   b. Two substances present, two phases present, all molecules are heteroatomic
   c. One phase present, two kinds of homoeoatomic molecules present
   d. One phase present, all molecules are triatomic, all molecules are identical

1.28 Indicate whether each of the following samples of matter is a heterogeneous mixture, a homogeneous mixture, a compound, or an element.
   a. A colorless gas, only part of which reacts with hot iron
   b. A “cloudy” liquid that separates into two layers upon standing for 2 hours
   c. A green solid, all of which melts at the same temperature to produce a liquid that decomposes upon further heating
   d. A colorless gas that cannot be separated into simpler substances using physical means and that reacts with copper to produce both a copper–nitrogen and a copper–oxygen compound

1.29 Classify each of the following pairs of substances as (1) two elements, (2) two compounds, (3) an element and a compound, or (4) a single pure substance.
   a. Q-X and Q-X
   b. Q-X and Q-X
   c. Q and X
   d. Q-X and Q-X

1.30 Write a formula for each of the following substances by using the information given about molecules of the substance.
   a. Molecules are triatomic and contain the elements hydrogen, carbon, and nitrogen.
   b. Molecules are heptatomic and contain 2 atoms of hydrogen, 1 atom of sulfur, and the element oxygen.
   c. Molecules are triatomic and contain twice as many atoms of nitrogen as of oxygen.
   d. Molecules are pentatomic and contain the elements hydrogen and nitrogen and 3 atoms of oxygen.

1.31 In each of the following pairs of formulas, indicate whether the first formula listed denotes more total atoms, the same number of total atoms, or fewer total atoms than the second formula listed.
   a. HN_3 and NH_3
   b. CaSO_4 and Mg(OH)_2
   c. NaClO_3 and Ba(CN)_2
   d. Ba_3(PO_4)_2 and Mg(C_2H_3O_2)_2

1.32 On the basis of the given information, determine the numerical value of the subscript x in each of the following chemical formulas.
   a. Ba_xS_2O_3; formula unit contains 6 atoms
   b. Al_x(SO_4)_3; formula unit contains 17 atoms
   c. SOCl_2; formula unit contains 5 atoms
   d. C_xH_2Cl_2; formula unit contains 8 atoms

1.33 A mixture contains the following five pure substances: N_2, N_2H_4, NH_3, CH_4, and CH_3Cl.
   a. How many different kinds of molecules that contain four or fewer atoms are present in the mixture?
   b. How many different kinds of atoms are present in the mixture?
   c. How many total atoms are present in a mixture sample containing five molecules of each component?
   d. How many total hydrogen atoms are present in a mixture sample containing four molecules of each component?

PRACTICE TEST True/False

1.34 An indefinite volume is a property of both gases and liquids.
1.35 When a substance undergoes a chemical change, it is always true that one or more new substances are produced.
1.36 The description "two substances present, two phases present" applies to all types of mixtures.
1.37 Scientists "suspect" that there are more naturally occurring elements yet to be discovered.
1.38 The chemical symbol for an element is always the first one or two letters in the element's name.
1.39 A compound results from the physical combination of two or more elements.
1.40 The most abundant elements in the universe and in Earth's crust are, respectively, hydrogen and oxygen.

1.41 Both homogeneous mixtures and heterogeneous mixtures can have a variable composition.

1.42 The descriptors homoatomic and triatomic both apply to molecules of the compound H₂O.

1.43 The properties "melts at 73°C" and "decomposes upon heating" are both examples of chemical properties of a substance.

1.44 A pure substance cannot be decomposed into simpler pure substances by chemical means.

1.45 The elements gold, silver, and aluminum all have two-letter chemical symbols.

1.46 The chemical formulas NH₃ and HN₃ both denote the same compound.

1.47 The total number of atoms present in one formula unit of (NH₄)₂PO₄ is 18.

1.48 A physical change is a process in which a substance changes its physical appearance but not its chemical composition.

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**PRACTICE TEST**  Multiple Choice

1.49 Which of the following is a property of both liquids and solids?
   a. Definite shape
   b. Definite volume
   c. Indefinite shape
   d. Indefinite volume

1.50 In which of the following pairs of properties do both properties chemical properties?
   a. Freezes at 0°C, flammable
   b. Decomposes at 75°C, reacts with chlorine
   c. Good reflector of light, blue in color
   d. Has a high density, is very hard

1.51 When a substance undergoes a chemical change, it is always true that
   a. It melts
   b. It changes physical state
   c. Its chemical composition changes
   d. Heat is evolved

1.52 Which of the following statements is correct?
   a. Elements, but not compounds, are pure substances.
   b. Compounds, but not elements, are pure substances.
   c. Both elements and compounds are pure substances.
   d. Neither elements nor compounds are pure substances.

1.53 A pure substance A is found to change upon heating into two new pure substances B and C. Both B and C may be decomposed by chemical means. From this, we may conclude that
   a. A is an element, and B and C are compounds
   b. A is a compound, and B and C are elements
   c. A, B, and C are all elements
   d. A, B, and C are all compounds

1.54 In which of the following sequences of elements do each of the elements have a one-letter chemical symbol?
   a. Lead, nitrogen, zinc
   b. Potassium, fluorange, carbon
   c. Tin, hydrogen, iodine
   d. Oxygen, silicon, chlorine

1.55 Which one of the following statements is incorrect?
   a. An atom is the smallest "piece" of an element that can exist and still have the properties of the element.
   b. Free isolated atoms are rarely encountered in nature.
   c. Atoms may be decomposed using chemical change.
   d. Only one kind of atom may be present in a homoatomic molecule.

1.56 Which of the following pairings of terms is incorrect?
   a. Element — homoatomic molecules
   b. Pure substance — variable composition
   c. Heterogeneous mixture — two or more regions with different properties
   d. Homogeneous mixture — two or more substances present

1.57 Which of the following classifications of matter could not contain heteratomic molecules?
   a. Heterogeneous mixture
   b. Homogeneous mixture
   c. Pure substance
   d. Element

1.58 In which of the following pairs of formulas do the two members of the pair contain the same number of elements as well as the same number of atoms?
   a. H₂ and HF
   b. COCl₂ and COCl₂
   c. SO₂ and SO₃
   d. NH₄Cl and BaSO₄