Matter, Measurement, and Problem Solving

The most incomprehensible thing about the universe is that it is comprehensible.

——Albert Einstein (1879—1955)

1.1 Atoms and Molecules 1
1.2 The Scientific Approach to Knowledge 3
1.3 The Classification of Matter 5
1.4 Physical and Chemical Changes and Physical and Chemical Properties 9
1.5 Energy: A Fundamental Part of Physical and Chemical Change 12
1.6 The Units of Measurement 13
1.7 The Reliability of a Measurement 20
1.8 Solving Chemical Problems 27
Key Learning Outcomes 36

WHAT DO YOU THINK is the most important idea in all of human knowledge? There are, of course, many possible answers to this question—some practical, some philosophical, and some scientific. If we limit ourselves only to scientific answers, mine would be this: the properties of matter are determined by the properties of atoms and molecules. Atoms and molecules determine how matter behaves—if they were different, matter would be different. The properties of water molecules determine how water behaves, the properties of sugar molecules determine how sugar behaves, and the properties of the molecules that compose our bodies determine how our bodies behave. The understanding of matter at the molecular level gives us unprecedented control over that matter. For example, our understanding of the details of the molecules that compose living organisms has revolutionized biology over the last 50 years.
1.1 Atoms and Molecules

The air over most U.S. cities, including my own, contains at least some pollution. A significant component of that pollution is carbon monoxide, a colorless gas emitted in the exhaust of cars and trucks. Carbon monoxide gas is composed of carbon monoxide molecules, each of which contains a carbon atom and an oxygen atom held together by a chemical bond. Atoms are the submicroscopic particles that constitute the fundamental building blocks of ordinary matter. Free atoms are rare in nature; instead they bind together in specific geometrical arrangements to form molecules.

The properties of the substances around us depend on the atoms and molecules that compose the substances, so the properties of carbon monoxide gas depend on the properties of carbon monoxide molecules. Carbon monoxide molecules happen to be just the right size and shape, and happen to have just the right chemical properties, to fit neatly into cavities within hemoglobin molecules in blood that normally carry oxygen molecules (Figure 1.1). Consequently, carbon monoxide diminishes the oxygen-carrying capacity of blood. Breathing air containing too much carbon monoxide (greater than 0.04% by volume) can lead to unconsciousness and even death because not enough
Hemoglobin, a large protein molecule, is the oxygen carrier in red blood cells. Each subunit of the hemoglobin molecule contains an iron atom to which oxygen binds. Carbon monoxide molecules can take the place of oxygen, thus reducing the amount of oxygen reaching the body’s tissues.

Oxygen reaches the brain. Carbon monoxide deaths can occur as a result of running an automobile in a closed garage or using a propane burner in an enclosed space for too long. In smaller amounts, carbon monoxide causes the heart and lungs to work harder and can result in headaches, dizziness, weakness, and confusion.

Cars and trucks emit another closely related molecule, called carbon dioxide, in far greater quantities than carbon monoxide. The only difference between carbon dioxide and carbon monoxide is that carbon dioxide molecules contain two oxygen atoms instead of just one. However, this extra oxygen atom dramatically affects the properties of the gas. We breathe much more carbon dioxide—which composes 0.04% of air, and is a product of our own respiration as well—than carbon monoxide, yet it does not kill us. Why? Because the presence of the second oxygen atom prevents carbon dioxide from binding to the oxygen-carrying site in hemoglobin, making it far less toxic. Although high levels of carbon dioxide (greater than 10% of air) can be hazardous for other reasons, lower levels can enter the bloodstream with no adverse effects. Such is the molecular world. Any differences between molecules—such as the extra oxygen atom in carbon monoxide—results in differences between the substances that the molecules compose.

As another example, consider two other closely related molecules, water and hydrogen peroxide:

A water molecule is composed of one oxygen atom and two hydrogen atoms. A hydrogen peroxide molecule is composed of two oxygen atoms and two hydrogen atoms. This seemingly small molecular difference results in a huge difference in the properties of water and hydrogen peroxide. Water is the familiar and stable liquid we all drink and bathe in. Hydrogen peroxide, in contrast, is an unstable liquid that, in its pure form, burns the skin on contact and is used in rocket fuel. When you pour water onto your hair, your hair simply becomes wet. However, if you put diluted hydrogen peroxide on your hair—which you may have done if you have ever bleached your hair—a chemical reaction occurs that strips your hair of its color.

The hydrogen peroxide we use as an antiseptic or bleaching agent is considerably diluted.
The details of how specific atoms bond to form a molecule—in a straight line, at a particular angle, in a ring, or in some other pattern—as well as the type of atoms in the molecule, determine everything about the substance that the molecule composes. If we want to understand the substances around us, we must understand the atoms and molecules that compose them—this is the central goal of chemistry. A good simple definition of chemistry is

Chemistry—the science that seeks to understand the behavior of matter by studying the behavior of atoms and molecules.

1.2 The Scientific Approach to Knowledge

Throughout history, humans have approached knowledge about the physical world in different ways. For example, the Greek philosopher Plato (427–347 B.C.) thought that the best way to learn about reality was not through the senses, but through reason. He believed that the physical world was an imperfect representation of a perfect and transcendent world (a world beyond space and time). For him, true knowledge came not through observing the real physical world, but through reasoning and thinking about the ideal one.

The scientific approach to knowledge, however, is exactly the opposite of Plato’s. Scientific knowledge is empirical—it is based on observation and experiment. Scientists observe and perform experiments on the physical world to learn about it. Some observations and experiments are qualitative (noting or describing how a process happens), but many are quantitative (measuring or quantifying something about the process). For example, Antoine Lavoisier (1743–1794), a French chemist who studied combustion (or burning), made careful measurements of the mass of objects before and after burning them in closed containers. He noticed that there was no change in the total mass of material within the container during combustion. In doing so, Lavoisier made an important observation about the physical world.

Observations often lead scientists to formulate a hypothesis, a tentative interpretation or explanation of the observations. For example, Lavoisier explained his observations on combustion by hypothesizing that when a substance burns, it combines with a component of air. A good hypothesis is falsifiable, which means that it makes predictions that can be confirmed or refuted by further observations. Scientists test hypotheses by experiments, highly controlled procedures designed to generate observations that may confirm or refute a hypothesis. The results of an experiment may support a hypothesis or prove it wrong—in which case the scientist must modify or discard the hypothesis.

In some cases, a series of similar observations leads to the development of a scientific law, a brief statement that summarizes past observations and predicts future ones. Lavoisier summarized his observations on combustion with the law of conservation of mass, which states, “In a chemical reaction, matter is neither created nor destroyed.” This statement summarized his observations on chemical reactions and predicted the outcome of future observations on reactions. Laws, like hypotheses, are also subject to experiments, which can support them or prove them wrong.

Scientific laws are not laws in the same sense as civil or governmental laws. Nature does not follow laws in the way that we obey the laws against speeding or running a stop sign. Rather, scientific laws describe how nature behaves—they are generalizations about what nature does. For that reason, some people find it more appropriate to refer to them as principles rather than laws.

One or more well-established hypotheses may form the basis for a scientific theory. A scientific theory is a model for the way nature is and tries to explain not merely what nature does but why. As such, well-established theories are the pinnacle of scientific knowledge, often predicting behavior far beyond the observations or laws from which they were developed. A good example of a theory is the atomic theory proposed by English chemist John Dalton (1766–1844). Dalton explained the law of conservation of mass, as well as other laws and observations of the time, by proposing that matter is composed of small, indestructible particles called atoms. Since these particles are merely rearranged in chemical changes (and not created or destroyed), the total amount of mass remains the same. Dalton’s theory is a model for the physical world—it gives us insight into how nature works and, therefore, explains our laws and observations.

The term atoms in this definition can be interpreted loosely to include atoms that have lost or gained electrons.

Although some Greek philosophers, such as Aristotle, did use observation to attain knowledge, they did not emphasize experiment and measurement to the extent that modern science does.

A painting of the French chemist Antoine Lavoisier with his wife, Marie, who helped him in his work by illustrating his experiments and translating scientific articles from English. Lavoisier, who also made significant contributions to agriculture, industry, education, and government administration, was executed during the French Revolution. (The Metropolitan Museum of Art)

In Dalton’s time, people thought atoms were indestructible. Today, because of nuclear reactions, we know that atoms can be broken apart into their smaller components.
Finally, the scientific approach returns to observation to test theories. For example, scientists can test the atomic theory by trying to isolate single atoms or by trying to image them (both of which, by the way, have already been accomplished). Theories are validated by experiments; however, theories can never be conclusively proven because some new observation or experiment always has the potential to reveal a flaw. Notice that the scientific approach to knowledge begins with observation and ends with observation. An experiment is in essence a highly controlled procedure for generating critical observations designed to test a theory or hypothesis. Each new set of observations has the potential to refine the original model. Figure 1.2 summarizes one way to map the scientific approach to knowledge. Scientific laws, hypotheses, and theories are all subject to continued experimentation. If a law, hypothesis, or theory is proved wrong by an experiment, it must be revised and tested with new experiments. Over time, the scientific community eliminates or corrects poor theories and laws, and valid theories and laws—those consistent with experimental results—remain.

Established theories with strong experimental support are the most powerful pieces of scientific knowledge. You may have heard the phrase “That is just a theory,” as if theories are easily dismissible. Such a statement reveals a deep misunderstanding of the nature of a scientific theory. Well-established theories are as close to truth as we get in science. The idea that all matter is made of atoms is “just a theory,” but it has over 200 years of experimental evidence to support it. It is a powerful piece of scientific knowledge on which many other scientific ideas have been built.

One last word about the scientific approach to knowledge: some people wrongly imagine science to be a strict set of rules and procedures that automatically lead to irrefutable, objective facts. This is not the case. Even our diagram of the scientific approach to knowledge is only an idealization of real science, useful to help us see the key distinctions of science. Real science requires hard work, care, creativity, and even a bit of luck. Scientific theories do not just arise out of data—men and women of great genius and creativity craft theories. A great theory is not unlike a master painting, and many see a similar kind of beauty in both. (For more on this aspect of science, see the box entitled Thomas S. Kuhn and Scientific Revolutions.)

Conceptual Connection 1.1 Laws and Theories

Which statement best explains the difference between a law and a theory?

(a) A law is truth; a theory is mere speculation.
(b) A law summarizes a series of related observations; a theory gives the underlying reasons for them.
(c) A theory describes what nature does; a law describes why nature does it.
The Nature of Science

Thomas S. Kuhn and Scientific Revolutions

When scientists talk about science, they often talk in ways that imply that their theories are “true.” Further, they talk as if they arrive at theories in logical and unbiased ways. For example, a theory central to chemistry that we have discussed in this chapter is John Dalton’s atomic theory—the idea that all matter is composed of atoms. Is this theory “true”? Was it reached in logical, unbiased ways? Will this theory still be around in 200 years?

The answers to these questions depend on how we view science and its development. One way to view science—let’s call it the traditional view—is as the continual accumulation of knowledge and the building of increasingly precise theories. In this view, a scientific theory is a model of the world that reflects what is actually in nature. New observations and experiments result in gradual adjustments to theories. Over time, theories get better, giving us a more accurate picture of the physical world.

In the twentieth century, a different view of scientific knowledge began to develop. A book by Thomas Kuhn, published in 1964 and entitled The Structure of Scientific Revolutions, challenged the traditional view. Kuhn’s ideas came from his study of the history of science, which he argued, does not support the idea that science progresses in a smooth cumulative way. According to Kuhn, science goes through fairly quiet periods that he called normal science. In these periods, scientists make their data fit the reigning theory, or paradigm. Small inconsistencies are swept aside during periods of normal science. However, when too many inconsistencies and anomalies develop, a crisis emerges. The crisis brings about a revolution and a new reigning theory. According to Kuhn, the new theory is usually quite different from the old one; it not only helps us to make sense of new or anomalous information, but also enables us to see accumulated data from the past in a dramatically new way.

Kuhn further contended that theories are held for reasons that are not always logical or unbiased, and that theories are not true models—in the sense of a one-to-one mapping—of the physical world. Because new theories are often so different from the ones they replace, he argued, and because old theories always make good sense to those holding them, they must not be “true” with a capital T; otherwise “true” would be constantly changing.

Kuhn’s ideas created a controversy among scientists and science historians that continues to this day. Some, especially postmodern philosophers of science, have taken Kuhn’s ideas one step further. They argue that scientific knowledge is completely biased and lacks any objectivity. Most scientists, including Kuhn, would disagree. Although Kuhn pointed out that scientific knowledge has arbitrary elements, he also said, “Observation ... can and must drastically restrict the range of admissible scientific belief, else there would be no science.” In other words, saying that science contains arbitrary elements is quite different from saying that science itself is arbitrary.

Question

In his book, Kuhn stated, “A new theory ... is seldom or never just an increment to what is already known.” Can you think of any examples that support Kuhn’s statement from your knowledge of the history of science? Do you know of any instances in which a new theory or model was drastically different from the one it replaced?

1.3 The Classification of Matter

Matter is anything that occupies space and has mass. This book, your desk, your chair, and even your body are all composed of matter. Less obviously, the air around you is also matter—it too occupies space and has mass. We call a specific instance of matter—such as air, water, or sand—a substance. We can classify matter according to its state (its physical form) and its composition (the basic components that make it up).

The States of Matter: Solid, Liquid, and Gas

Matter can exist in three different states: solid, liquid, and gas. In solid matter, atoms or molecules pack close to each other in fixed locations. Although the atoms and molecules in a solid vibrate, they do not move around or past each other. Consequently, a solid has a fixed volume and rigid shape. Ice, aluminum, and diamond are good examples of solids. Solid matter may be crystalline, in which case its atoms or molecules are in patterns with long-range, repeating order (Figure 1.3•), or it may be amorphous, in which case its atoms or molecules do not have any long-range order. Table salt and diamond are examples of crystalline solids; the well-ordered geometric shapes of salt and diamond crystals reflect the well-ordered geometric arrangement of their atoms (although this is not the case for all crystalline solids). Examples of amorphous solids include glass and plastic. In liquid matter, atoms or molecules pack about as closely as they do in solid

The state of matter changes from solid to liquid to gas with increasing temperature.

Glass and other amorphous solids can be thought of, from one point of view, as intermediate between solids and liquids. Their atoms are fixed in position at room temperature, but they have no long-range structure and do not have distinct melting points.
In a solid, the atoms or molecules are fixed in place and can only vibrate. In a liquid, although the atoms or molecules are closely packed, they can move past one another, allowing the liquid to flow and assume the shape of its container. In a gas, the atoms or molecules are widely spaced, making gases compressible as well as fluid (able to flow).

**Crystalline Solid:**
Regular three-dimensional pattern

**Solid matter**

**Liquid matter**

**Gaseous matter**

 matter, but they are free to move relative to each other, giving liquids a fixed volume but not a fixed shape. Liquids assume the shape of their container. Water, alcohol, and gasoline are all substances that are liquids at room temperature.

In *gaseous matter*, atoms or molecules have a lot of space between them and are free to move relative to one another, making gases *compressible* (Figure 1.4). When you squeeze a balloon or sit down on an air mattress, you force the atoms and molecules into a smaller space so that they are closer together. Gases always assume the shape and volume of their container. Substances that are gases at room temperature include helium, nitrogen (the main component of air), and carbon dioxide.

**Diamond**
C (s, diamond)

**FIGURE 1.3** Crystalline Solid
Diamond is a crystalline solid composed of carbon atoms arranged in a regular, repeating pattern.

**FIGURE 1.4** The Compressibility of Gases
Gases can be compressed—squeezed into a smaller volume—because there is so much empty space between atoms or molecules in the gaseous state.
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, as shown in the following chart:

The first division in the classification of matter is between a pure substance and a mixture. A pure substance is made up of only one component and its composition is invariant (it does not vary from one sample to another). The components of a pure substance can be individual atoms or groups of atoms joined together. For example, helium, water, and table salt (sodium chloride) are all pure substances. Each of these substances is made up of only one component: helium is made up of helium atoms, water is made up of water molecules, and sodium chloride is made up of sodium chloride units. The composition of a pure sample of any one of these is always exactly the same (because you can’t vary the composition of a substance made up of only one component).

A mixture, by contrast, is composed of two or more components in proportions that can vary from one sample to another. For example, sweetened tea, composed primarily of water molecules and sugar molecules (with a few other substances mixed in), is a mixture. We can make tea slightly sweet (a small proportion of sugar to water) or very sweet (a large proportion of sugar to water) or any level of sweetness in between.

We can categorize pure substances themselves into two types—elements and compounds—depending on whether or not they can be broken down (or decomposed) into simpler substances. Helium, which we just noted is a pure substance, is also a good example of an element, a substance that cannot be chemically broken down into simpler substances. Water, also a pure substance, is a good example of a compound, a substance composed of two or more elements (in this case hydrogen and oxygen) in a fixed, definite proportion. On Earth, compounds are more common than pure elements because most elements combine with other elements to form compounds.

We can also categorize mixtures into two types—heterogeneous and homogeneous—depending on how uniformly the substances within them mix. Wet sand is a heterogeneous mixture, one in which the composition varies from one region of the mixture to another.
Sweetened tea is a **homogeneous mixture**, one with the same composition throughout. Homogeneous mixtures have uniform compositions because the atoms or molecules that compose them mix uniformly. Heterogeneous mixtures are made up of distinct regions because the atoms or molecules that compose them separate. Here again we see that the properties of matter are determined by the atoms or molecules that compose it.

Classifying a substance according to its composition is not always obvious and requires that we either know the true composition of the substance or are able to test it in a laboratory. For now, we will focus on relatively common substances that you are likely to have encountered. Throughout this course, you will gain the knowledge to understand the composition of a larger variety of substances.

**Conceptual Connection 1.2 Pure Substances and Mixtures**

Let a small circle represent an atom of one type of element and a small square represent an atom of a second type of element. Make a drawing of (a) a pure substance (a compound) composed of the two elements (in a one-to-one ratio), (b) a homogeneous mixture composed of the two elements, and (c) a heterogeneous mixture composed of the two elements.

**Separating Mixtures**

Chemists often want to separate a mixture into its 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 physical or chemical properties. We can use various techniques that exploit these differences to achieve separation. For example, we can separate a mixture of sand and water by **decanting**—carefully pouring off—the water into another container. A homogeneous mixture of 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 condensed in a condenser and collected in a separate flask (Figure 1.5\(^*\)). If a mixture is composed of an insoluble solid and a liquid, we can separate the two by **filtration**, in which the mixture is poured through filter paper in a funnel (Figure 1.6\(^*\)).

**Distillation**

Most volatile component boils first.

- Mixture of liquids with different boiling points
- Cooling water out
- Mixture of liquids in
- Cooling water in
- Vapor collected as pure liquid

**Filtration**

- Stirring rod
- Mixture of liquid and solid
- Funnel
- Filter paper traps solid.
- Liquid component passes through and is collected.
1.4 Physical and Chemical Changes and Physical and Chemical Properties

Every day we witness changes in matter: ice melts, iron rusts, gasoline burns, fruit ripens, and water evaporates. What happens to the molecules or atoms that compose these samples of matter during such changes? The answer depends on the type of change. Changes that alter only state or appearance, but not composition, are physical changes. The atoms or molecules that compose a substance do not change their identity during a physical change. For example, when water boils, it changes its state from a liquid to a gas, but the gas remains composed of water molecules, so this is a physical change (Figure 1.7).

In contrast, changes that alter the composition of matter are chemical changes. During a chemical change, atoms rearrange, transforming the original substances into different substances. For example, the rusting of iron is a chemical change. The atoms that compose iron (iron atoms) combine with oxygen molecules from air to form iron oxide, the orange substance we call rust (Figure 1.8). Some other examples of physical and chemical changes are shown in Figure 1.9.

Physical and chemical changes are manifestations of physical and chemical properties. A physical property is a property that a substance displays without changing its composition, whereas a chemical property is a property that a substance displays only by changing its composition via a chemical change. The smell of gasoline is a physical property—gasoline does not change its composition when it exhibits its odor. The flammability of gasoline, in contrast, is a chemical property—gasoline does change its composition when it burns, turning into completely new substances (primarily carbon dioxide and water). Physical properties include odor, taste, color, appearance, melting point, boiling point, and density. Chemical properties include corrosiveness, flammability, acidity, toxicity, and other such characteristics.

**Figure 1.7 Boiling, a Physical Change**  When water boils, it turns into a gas but does not alter its chemical identity—the water molecules are the same in both the liquid and gaseous states. Boiling is thus a physical change, and the boiling point of water is a physical property.

**A physical change results in a different form of the same substance, while a chemical change results in a completely different substance.**

**Figure 1.8 Rusting, a Chemical Change**  When iron rusts, the iron atoms combine with oxygen atoms to form a different chemical substance, the compound iron oxide. Rusting is therefore a chemical change, and the tendency of iron to rust is a chemical property.