

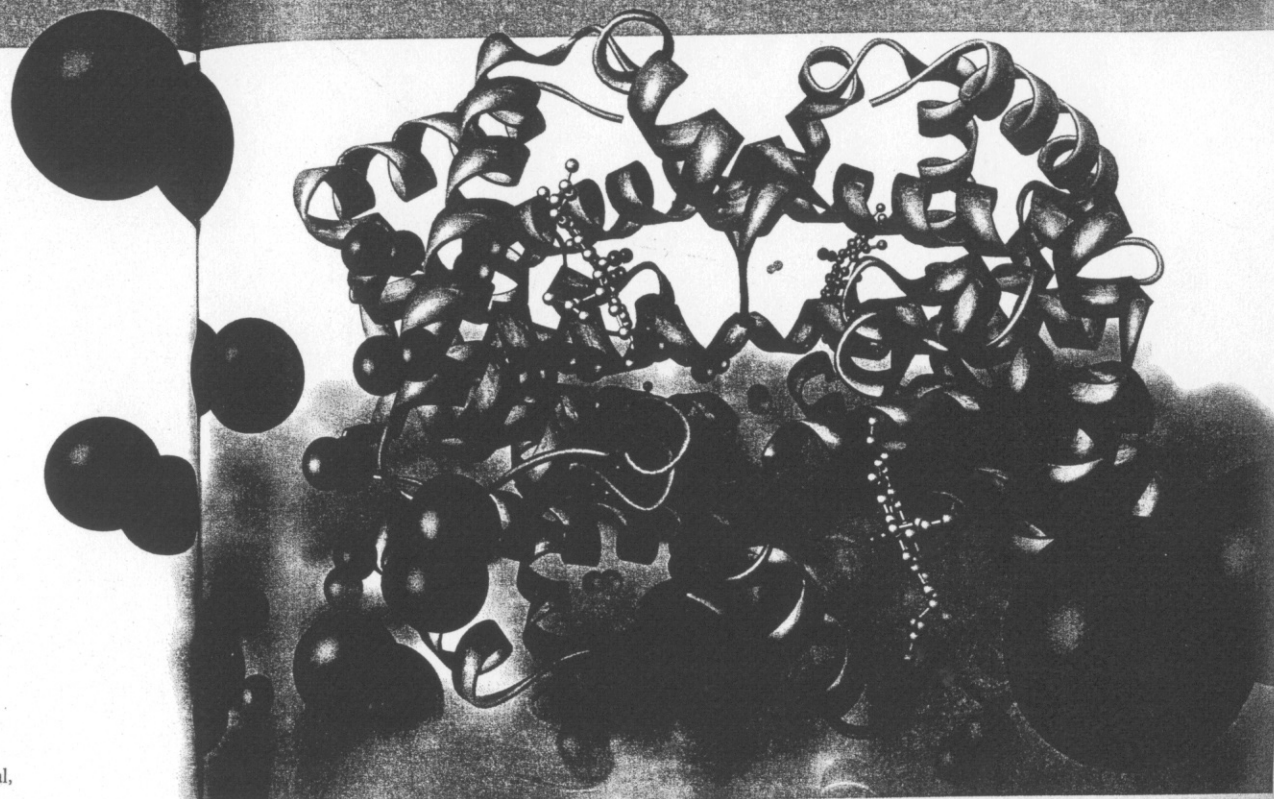
Matter, Measurement, and Problem Solving

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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 molecules and atoms.** Atoms and molecules determine how matter behaves—if they were different, matter would be different. The properties of water molecules, for example, determine how water behaves; the properties of sugar molecules determine how sugar behaves; and 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, the revolution that has occurred in biology over the last 50 years can be largely attributed to understanding the details of the molecules that compose living organisms.

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

—ALBERT EINSTEIN (1879–1955)

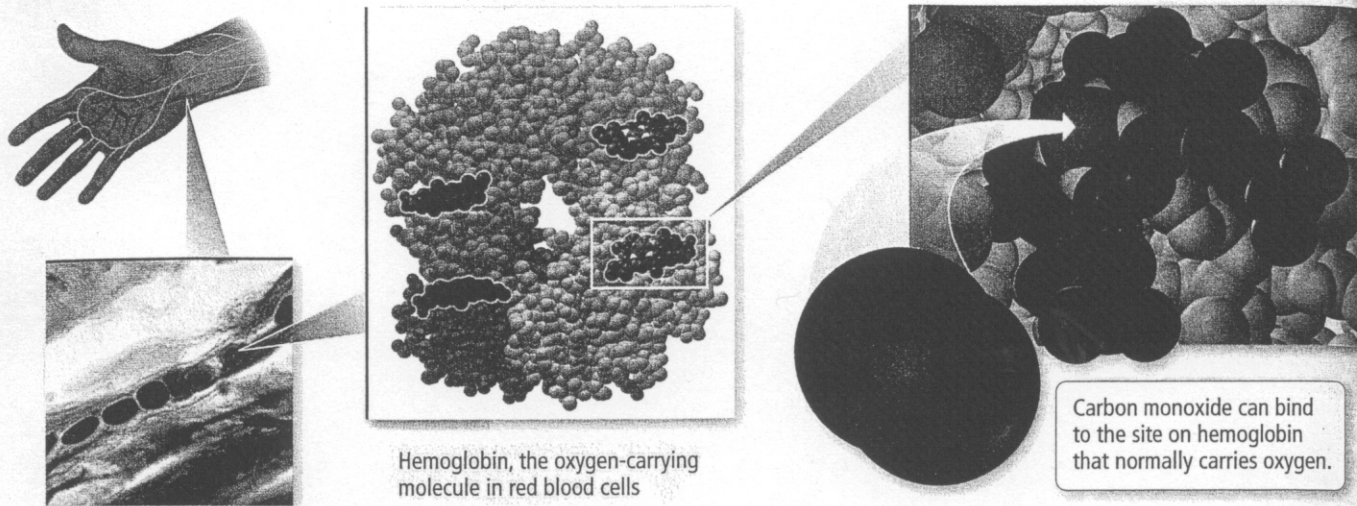


Hemoglobin, the oxygen-carrying protein in blood (depicted schematically above), can also bind carbon monoxide molecules (the linked red and black spheres).

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. They are most often found in **molecules**, two or more atoms joined in a specific geometrical arrangement.

The properties of the substances around us depend on the atoms and molecules that compose them, 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—the oxygen-carrying molecule in blood—that are

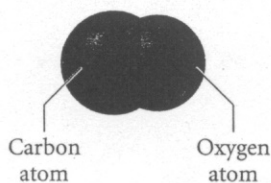


Hemoglobin, the oxygen-carrying molecule in red blood cells

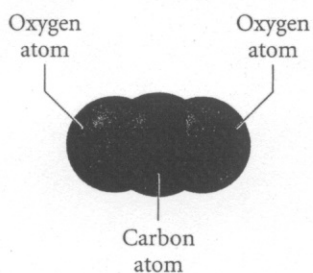
Carbon monoxide can bind to the site on hemoglobin that normally carries oxygen.

▲ **FIGURE 1.1 Binding of Oxygen and Carbon Monoxide to Hemoglobin** 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.

Carbon monoxide molecule



Carbon dioxide molecule

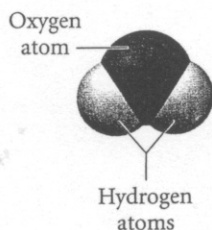


normally reserved for oxygen molecules (Figure 1.1 ▲). Consequently, carbon monoxide diminishes the oxygen-carrying capacity of blood. Breathing air containing too much carbon monoxide (greater than 0.04% by volume) can lead to unconsciousness and even death because not enough oxygen reaches the brain. Carbon monoxide deaths have occurred, for example, 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 headache, dizziness, weakness, and confused thinking.

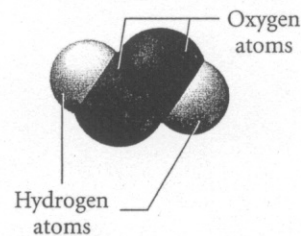
Cars and trucks emit another closely related molecule, called carbon dioxide, in far greater quantities than carbon monoxide. The only difference between carbon dioxide and carbon monoxide is that carbon dioxide molecules contain two oxygen atoms instead of just one. However, this extra oxygen atom dramatically affects the properties of the gas. We breathe much more carbon dioxide—which is naturally 0.03% of air, and 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 toxic for other reasons, lower levels can enter the bloodstream with no adverse effects. Such is the molecular world. Any changes in molecules—such as the addition of an oxygen atom to carbon monoxide—are likely to result in large changes in the properties of the substances they compose.

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

Water molecule



Hydrogen peroxide molecule



In the study of chemistry, atoms are often portrayed as colored spheres, with each color representing a different kind of atom. For example, a black sphere represents a carbon atom, a red sphere represents an oxygen atom, and a white sphere represents a hydrogen atom. For a complete color code of atoms, see Appendix IIA.

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 between 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 hydrogen peroxide in your hair—which you may have done if you have bleached your hair—a chemical reaction occurs that turns your hair blonde.

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, therefore,

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—that is, 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, 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. Lavoisier made an important *observation* about the physical world.

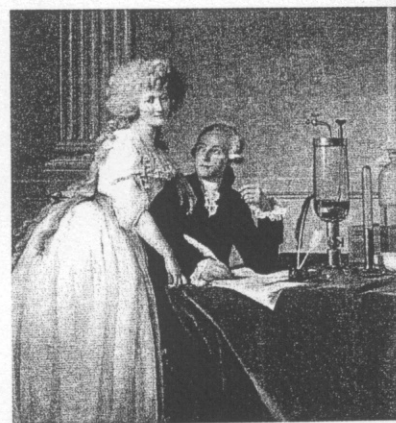
Observations often lead scientists to formulate a **hypothesis**, a tentative interpretation or explanation of the observations. For example, Lavoisier explained his observations on combustion by hypothesizing that when a substance combusts, it combines with a component of air. A good hypothesis is *falsifiable*, which means that it makes predictions that can be confirmed or refuted by further observations. Hypotheses are tested by **experiments**, highly controlled procedures designed to generate such observations. The results of an experiment may support a hypothesis or prove it wrong—in which case the hypothesis must be modified or discarded.

In some cases, a series of similar observations can lead to the development of a **scientific law**, a brief statement that summarizes past observations and predicts future ones. For example, 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 Lavoisier's observations on chemical reactions and predicted the outcome of future observations on reactions. Laws, like hypotheses, are also subject to experiments, which can add support to 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 passing on the right. 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*.

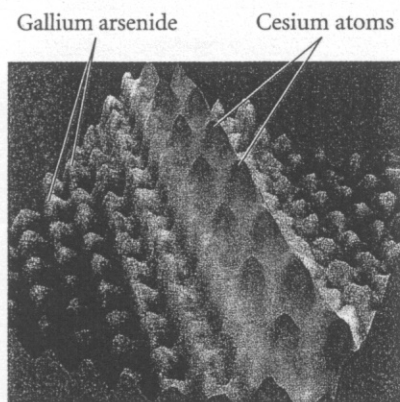
The hydrogen peroxide used as an antiseptic or bleaching agent is considerably diluted.

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, atoms were thought to be indestructible. Today, because of nuclear reactions, we know that atoms can be broken apart into their smaller components.



▲ Dalton's atomic theory has been validated in many ways, including the actual imaging of atoms by means of the scanning tunneling microscope (STM).

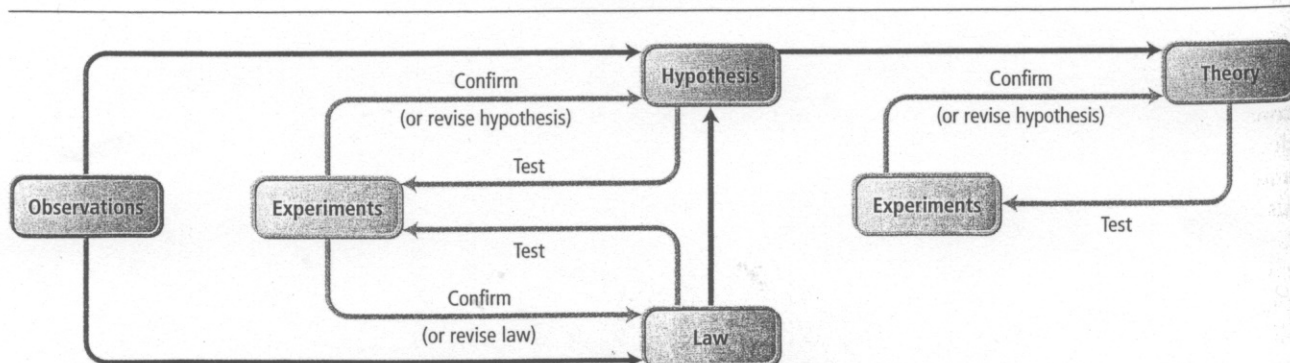
One or more well-established hypotheses may form the basis for a scientific **theory**. A scientific theory is a model for the way nature is and tries to explain not merely what nature does but why. As such, well-established theories are the pinnacle of scientific knowledge, often predicting behavior 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 was composed of small, indestructible particles called atoms. Since these particles were merely rearranged in chemical changes (and not created or destroyed), the total amount of mass would remain 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.

Finally, the scientific approach returns to observation to test theories. Theories are validated by experiments, though they can never be conclusively proved—there is always the possibility that a new observation or experiment will reveal a flaw. For example, the atomic theory can be tested by trying to isolate single atoms, or by trying to image them (both of which, by the way, have already been accomplished). Notice that the scientific approach to knowledge begins with observation and ends with observation, because an experiment is simply a highly controlled procedure for generating critical observations designed to test a theory or hypothesis. Each new set of observations allows refinement of the original model. This approach, often called the **scientific method**, is summarized in Figure 1.2 ▼. 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, poor theories and laws are eliminated or corrected and good 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 were easily dismissible. However, 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 method: some people wrongly imagine science to be a strict set of rules and procedures that automatically lead to inarguable, objective facts. This is not the case. Even our diagram of the scientific method is only an idealization of real science, useful to help us see the key distinctions of science. Doing real science requires hard work, care, creativity, and even a bit of luck. Scientific theories do not just fall out of data—they are crafted by men and women of great genius and creativity. 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*.)

The Scientific Method



▲ FIGURE 1.2 The Scientific Method

Conceptual Connection 1.1 Laws and Theories

Which of the following best explains the difference between a law and a theory?

- (a) A law is truth whereas a theory is mere speculation.
- (b) A law summarizes a series of related observations, while 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, we often talk in ways that imply that our theories are “true.” Further, we talk as if we arrive at theories in logical and unbiased ways. For example, a central theory to chemistry 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 you 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, however, a different view of scientific knowledge began to develop. In particular, a book by Thomas Kuhn, entitled *The Structure of Scientific Revolutions*, challenged the traditional view. Kuhn’s ideas came from his study of the history of science, which, he argues, does not support the idea that science progresses in a smooth cumulative way. According to Kuhn, science goes through fairly quiet periods that he calls *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 contends 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 argues, and because old theories always make good sense to those holding them, they must not be “True” with a capital T, otherwise “truth” 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 points out that scientific knowledge has *arbitrary elements*, he also says, “*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 states, “*A new theory . . . is seldom or never just an increment to what is already known.*” Can you think of any examples of this from your knowledge of the history of science? In other words, can you think of instances in which a new theory or model was drastically different from the one it replaced?