Addison-Wesley

Chemistry

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Cover photo:
A yellow precipitate of cadmium sulfide, CdS, forms spontaneously when clear aqueous solutions of sodium sulfide, Na_2S, and cadmium nitrate, $Cd(NO_3)_2$, are mixed.
Caution: *Sodium sulfide is an irritant. Avoid skin or eye contact with this and all other chemicals.*
Photo taken expressly for Addison-Wesley by Stephen Frisch.

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Chapter Preview

1·1 Chemistry

Chemists work at an amazing variety of jobs. Some develop new products such as textiles, paints, medicines, or cosmetics. Others may find methods to reduce pollution or to clean up the environment. A specialized chemist may be called on to identify and interpret the evidence found at the scene of a crime. Many chemists teach. Others do analyses of substances or check the quality of manufactured products. What all of these people have in common is a knowledge of chemistry.

Chemistry is a natural science.

Chemistry *is the study of the composition of substances and the changes that substances undergo*. Our world is complex. Chemistry reflects this complexity in the broad areas of interest that it covers. It contributes to other natural sciences including biology, geology, and physics. Chemistry overlaps with agriculture, medicine, and many manufacturing industries as well.

Most of the careers just mentioned apply a knowledge of chemistry to attain specific goals. These are examples of applied chemistry, or chemical technology. Pure chemistry, like other pure sciences, accumulates knowledge for its own sake. Pure science is neither good nor bad. Applied chemistry focuses on the uses of chemical knowledge. Technology can use scientific knowledge in ways that benefit or harm people or the environment. The political and social debates about the uses of scientific knowledge are really debates about technology.

Because chemistry is so diverse, it is usually considered to have five major divisions. With a few exceptions, **organic chemistry** *is the study of*

Figure 1·1
Chemical changes are responsible for many of the spectacular events around us. Here molten lava is being ejected from the Hawaiian volcano Kilauea.

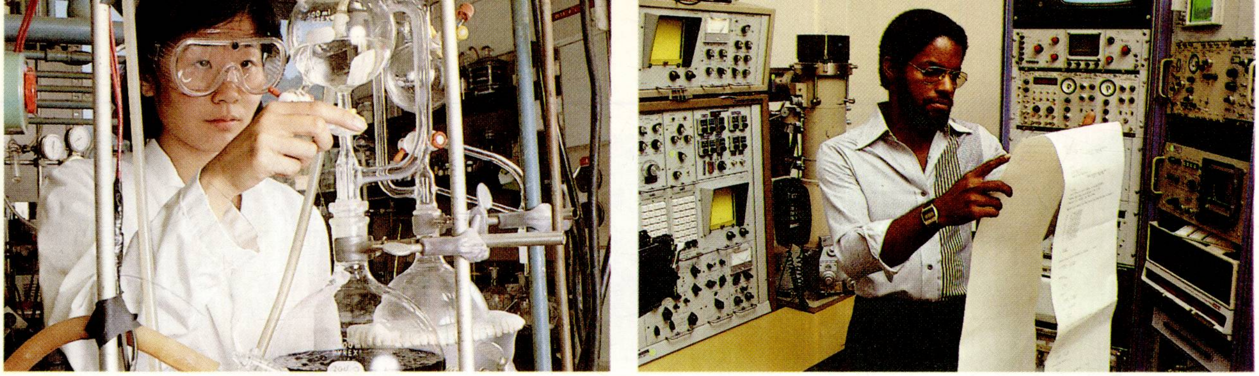


Figure 1·2
Glassware is used extensively in a "wet chemistry" laboratory. Most laboratories now use many automated electronic instruments to do chemical analyses.

essentially all substances containing carbon. It was originally the study of substances from living organisms. **Inorganic chemistry** *specializes in substances without carbon*. These are mainly substances from nonliving things. **Analytical chemistry** *is concerned primarily with the composition of substances*. Finding the amount of silver in an ore or minute quantities of a substance in a blood sample requires the practice of analytical chemistry. **Physical chemistry** *specializes in the discovery and description of the theoretical basis of the behavior of chemical substances*. Usually it relies heavily on mathematics. **Biochemistry** *is the study of the composition and changes in composition of living organisms*. Obviously, these five subdivisions of chemistry overlap. For example, one cannot measure a change in an organic or inorganic substance without some proficiency in analytical chemistry.

Figure 1·3
After designing a chemical processing system, a chemical engineer must be able to explain the system's features.

1·A Chemical Technology

To meet the needs of our modern world, enormous quantities of chemicals are manufactured every year. These include fertilizers, fuels, pesticides, textiles, plastics, and other materials. Working with ordinary laboratory glassware, chemists develop the processes for producing small amounts of these chemicals. It is the job of the chemical engineer to plan and carry out the same reactions on a large scale.

Chemical engineers are employed by many industries. They work for companies that produce fuels, metals, rubber, cosmetics, drugs, paper, paints, and foods. Chemical engineers must determine whether a reaction can be used for mass production. They plan the layout of a plant, design equipment for it, and supervise its construction and operation. Often they are asked to redesign an existing plant to increase productivity. They may add new safety or pollution control features. Because they are responsible for the efficient operation of the plant, they must always be aware of costs.

Many engineering and technical schools offer degrees in chemical engineering. The course of study emphasizes chemistry, physics, mathematics, economics, writing, and the use of computers. Specialized engineering courses are also required.

1·2 The Scientific Method

The scientific method helps scientists answer questions about the physical universe.

Like most fields of human endeavor, science has evolved formal and time-tested methods to solve problems. The scientific method is one important approach. It was through the scientific method that many of the chemical elements were first discovered. *The* **scientific method** *incorporates observations, hypotheses, experiments, theories, and laws. Scientists make* **observations** *when they note and record facts about natural phenomena.* They try to explain their observations by devising hypotheses. **Hypotheses** *are descriptive models for observations.* A hypothesis is useful if it accounts for what scientists observe in many situations.

In order to learn more, *scientists often perform* **experiments** *in which one or more of the conditions are controlled.* An important principle of an experiment is that it can be repeated numerous times. *The observations, which are recorded from an experiment, constitute* **data.** When observations or experimental data do not fit the hypothesis, it must be scrapped or adjusted. The new or refined hypothesis is then subjected to further experimental testing. An important interplay takes place between hypotheses and experiments. The hypothesis guides the design of new experiments. At the same time, experiments guide the rejection or refinement of the hypothesis.

When viewing the world, a scientist is interested in both what is happening and why it is happening.

Once a hypothesis meets the test of repeated experimentation, it may be elevated to a theory. *A* **theory** *is a thoroughly tested model that explains why experiments give certain results.* A theory can never be proved. Nevertheless, theories are very useful because they help us to form mental pictures of objects or processes that cannot be seen. Moreover they give us the power to predict the behavior of natural systems under circumstances that are different from those of the original observations.

Occasionally a widely held scientific theory must be modified to agree with new experimental evidence. This is usually the cause of much excitement in the scientific community.

Another product of scientific research is a law. *A* **scientific law** *is a concise statement that summarizes the results of a broad variety of observations and experiments.* A scientific law is different from a theory in that it only describes a natural phenomenon. It does not attempt to explain it. Scientific laws can often be expressed by simple mathematical relationships. They usually concern natural behaviors that are not immediately obvious. For most people a statement like Boyle's law: "The volume of a gas is inversely proportional to the pressure exerted on it" meets these criteria.

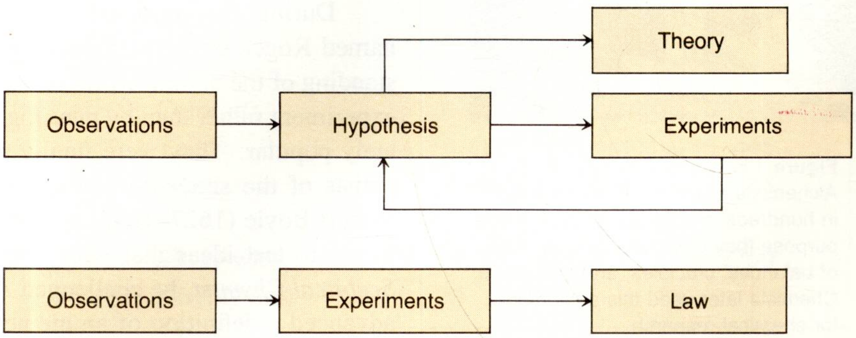


Figure 1·4
This outline of the scientific method shows how experimental observations lead to the development of hypotheses and theories. A scientific law summarizes the results of many experiments, but it does not explain why a behavior is observed; that is the role of the hypothesis and the theory.

Problem

1. Classify each of the following statements as an example of experiment, hypothesis, theory, or law.
   a. The ashes from a campfire weigh less than the wood that was burned. Therefore mass is destroyed (or lost) when wood is burned.
   b. A body at rest tends to remain at rest.
   c. Water boils at 100°C on your kitchen stove and in the laboratory.
   d. All matter is composed of atoms, which themselves are composed of protons, electrons, and neutrons.

1·B Alchemy and the Birth of Chemistry

Long before the science of chemistry existed, people made use of chemical reactions to dye cloth, tan leather, and prepare foods. Eventually people began to search for explanations for the structure and behavior of matter. Greek philosophers 2500 years ago believed that knowledge of the natural world could be achieved through pure reasoning. One group, the "Atomists," proposed that matter was made of tiny indivisible particles called atoms. The famous philosopher Aristotle disagreed. He said that matter was composed of four elements: fire, air, water, and earth. Because of Aristotle's fame and reputation, much of the world agreed with his ideas. As a result, the idea of atoms was not discussed seriously for more than 2000 years.

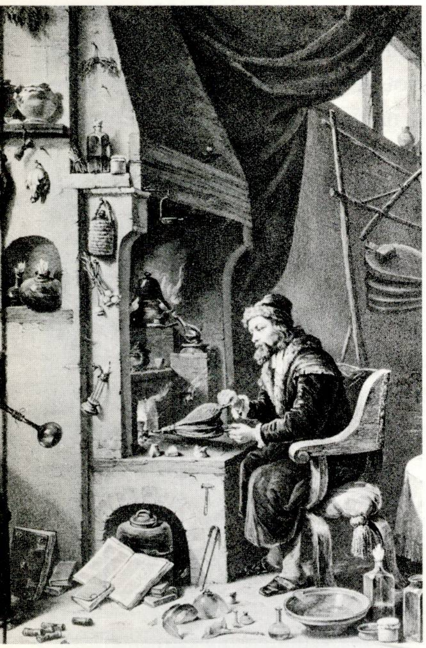


Figure 1·5
Alchemists mixed materials together in hundreds of different ways. For this purpose they designed various types of balances, crucibles, and glassware. Chemists later used this equipment for chemical research.

With the destruction of Greek civilization, European science fell into disrepair and did not reappear until the Middle Ages. This period saw the rise of the alchemists. Their goal was to change common metals into gold. Although the alchemists were unable to succeed in their quest, they did spur the development of science. They developed many experimental procedures and laboratory apparatus. Through trial and error they also developed a wealth of knowledge about the characteristics of substances.

During the thirteenth century, an English Franciscan monk named Roger Bacon introduced a new idea. He held that an understanding of the natural world could be gained through observation and experiment rather than by pure logic. Bacon's ideas were not immediately popular. They were finally put into practice, however, by scientists of the sixteenth and seventeenth centuries. The Englishman Robert Boyle (1627–1691) emphasized the necessity of using experiments to test ideas that were obtained by reason. In his book, *The Sceptical Chymist,* he challenged Aristotle's four "elements." He also advanced a definition of an element very similar to that used today.

Antoine Lavoisier (1743–1794) took an important new step in the process of experimentation. This was to make precise measurements of the mass changes in chemical reactions. His experiments transformed chemistry from a science of observation to the science of measurement that it is today. For this reason, Lavoisier is often called the founder of modern chemistry.

Figure 1·6
This nineteenth century chemical laboratory was named after Lavoisier, the great eighteenth century chemist.

1·3 Properties of Matter

The material things around us are all various types of matter. **Matter** *is anything that takes up space and has mass*. Aluminum, water, air, glass, and you are different kinds of matter. Ideas, light, and heat are not matter. They do not take up space or have mass. *The amount of matter that an object contains is its* **mass.** A golf ball has more mass than a table tennis ball. It contains more matter.

Some materials are composed of numerous types of matter; others consist of a single kind. *A* **substance** *is a particular kind of matter that has a uniform and definite composition*. Table sugar is a substance. It is 100% sucrose. Substances are often called pure substances. Lemonade is not a substance. It contains different amounts of sugar and lemon juice in water.

All samples of a substance have identical properties. A **physical property** *is a quality or condition of a substance that can be observed or measured without changing the substance's composition*. It can be specified without reference to any other substance. Some physical properties of matter include color, solubility, mass, odor, hardness, density, electrical conductivity, magnetism, melting point, and boiling point. Physical properties help chemists identify substances (Table 1·1). A colorless odorless liquid in which both salt and sugar dissolve and that boils at 100°C is probably water. Another colorless liquid that has a distinctive odor, that evaporates quickly when placed on your skin, and in which salt will not dissolve is most certainly not water.

Every substance has a unique set of physical properties.

Table 1·1 Physical Properties of Some Common Substances

Substance	State (at normal conditions)	Color	Melting point (°C)	Boiling point (°C)
Oxygen	Gas	Colorless	−218	−183
Bromine	Liquid	Red-brown	−7	59
Water	Liquid	Colorless	0	100
Sulfur	Solid	Yellow	113	445
Sodium chloride (table salt)	Solid	White	801	1413
Iron	Solid	Silver-white (freshly cut)	1535	2750

1·4 The States of Matter

Under normal laboratory conditions matter can exist in three physical states.

Matter can exist in three different physical states: solid, liquid, and gas. The physical state of a substance is a physical property of that substance. Certain characteristics summarized in Table 1·2 distinguish each state of matter.

A **solid** *is matter that has a definite shape and volume*. The shape of a solid does not depend on the shape of the container (Figure 1·7). Solids usually have a high density, and they expand only slightly when heated. They are almost incompressible. Coal, sugar, bone, ice, and iron are examples of solids.

A **liquid** *is a form of matter that flows, has a fixed volume, and takes the shape of its container*. Liquids are generally less dense than solids. They expand slightly when heated and are almost incompressible. Examples of liquids are water, milk, and blood.

Safety

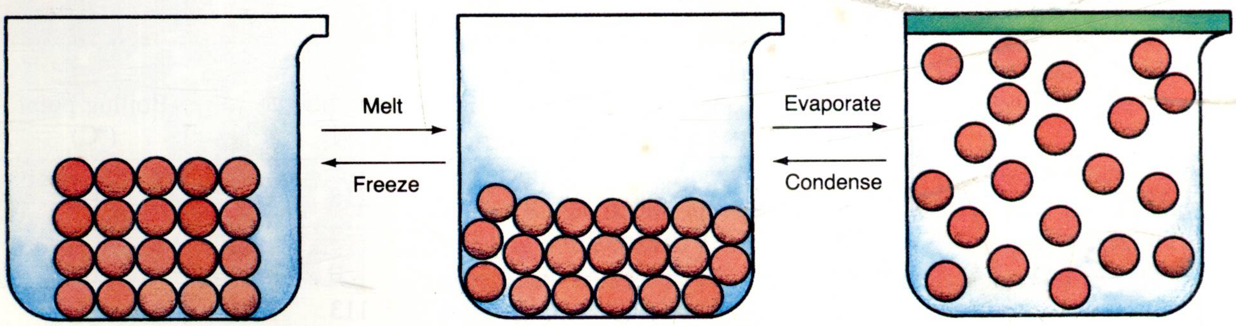
Gases expand dramatically when heated. Never heat a tightly closed vessel, as the build-up in gas pressure may cause an explosion.

A **gas** *is matter that takes both the shape and the volume of its container*. Gases expand without limit to fill any space and are easily compressed. The term *gas* is limited to those substances that exist in the gaseous state at room temperature. For example, air is a mixture of gases including oxygen and nitrogen. *The word* **vapor** *describes a substance that, although in the gaseous state, is generally a liquid or solid at room temperature*. Steam, the gaseous form of water, is a vapor. Moist air contains water vapor. The words *gas* and *vapor* should not be used interchangeably; there is a difference.

A fourth state of matter, plasma, exists only at very high temperatures. Most of the matter in the universe is plasma because stars are in a plasma state.

Problem

2. What is the physical state of each of the following at room temperature? **a.** silver **b.** gasoline **c.** helium **d.** paraffin wax **e.** rubbing alcohol



a Solid **b** Liquid **c** Gas

Figure 1·7
The three states of matter differ because of the arrangement of their particles. **a** A solid has its own shape and volume. **b** A liquid conforms to the shape but not the volume of its container. **c** A gas will occupy all the volume of its container.