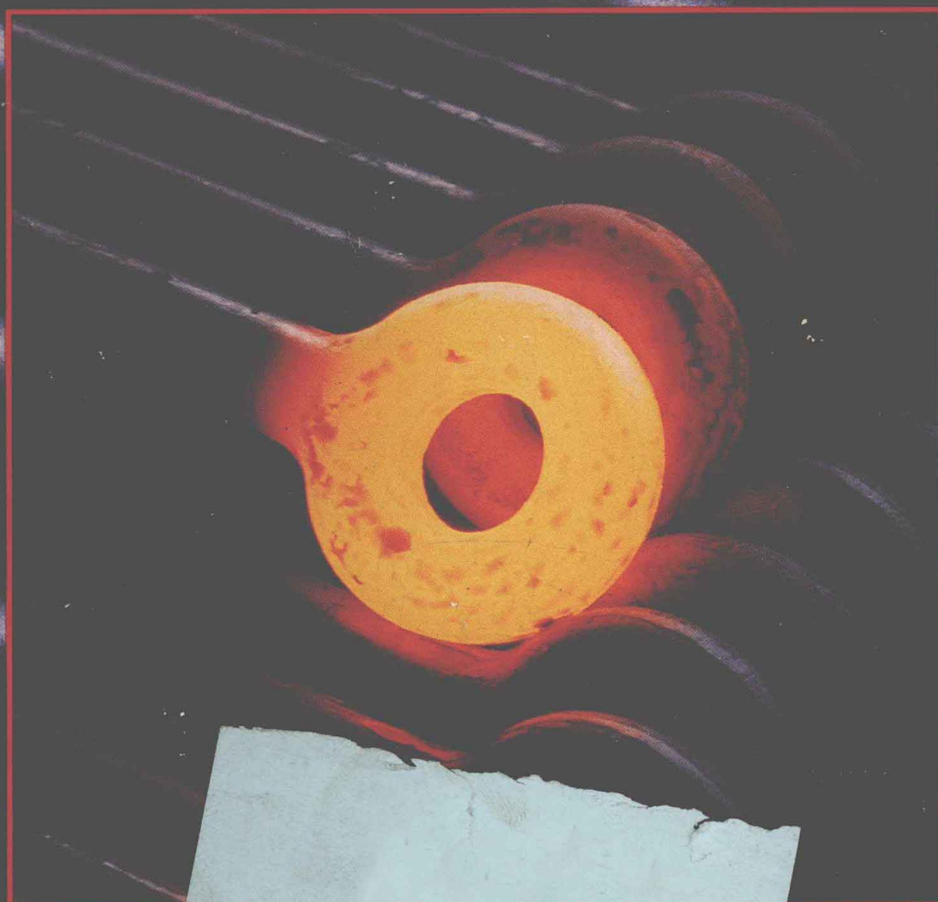
CHEMISTRY INDUSTRY AND THE ENVIRONMENT



Chemistry, Industry and the Environment

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CHEMISTRY INDUSTRY AND THE ENVIRONMENT

PREFACE

This text was written for a one-semester course taken by non-science majors seeking to both satisfy a science requirement and gain some exposure to chemistry at a college level. Students reading this text will gain insight into the processes of science and an appreciation of the understandings that science offers.

The book was written with the conviction that chemistry offers important insights into both the benefits of technology and the environmental problems that accompany the use of this technology. It differs from the author's earlier text, *Worlds of Chemistry,* in its greater emphasis on the impact that science and technology have on our lives and on the quality of our environment. I hope that students using this text will increase their awareness and understanding of environmental issues so they might make more informed choices in their personal and public lives.

This text, in its early chapters, presents some of the history of chemistry. Many of the early experiments that enabled scientists to propose theories about atoms and molecules are simple in concept. I present some of the reasoning from experimental evidence that marked the development of ideas concerning atomic structure and chemical bonding. I also make some of the philosophy of science explicit. Students can better understand science by knowing some of its history, and they can better relate their study of science to other disciplines when its methodology is considered.

Applications are used to make concepts come alive for students and to arouse student interest in the underlying chemistry. In contrast with other texts for non-science students, I have presented fewer examples and sought to develop more complete connections between concepts and applications. For example, material on buffers is presented without using equilibrium calculations. The use of radioactive isotopes to estimate the age of the earth and the use of carbon-14 dating to trace human history illustrate nuclear decay reactions. A consideration of the rates of chemical reactions leads into a discussion of enzyme-catalyzed reactions and the mode of action of sulfa and penicillin. The control of automobile emissions is discussed when introducing the concepts of energy and entropy. The examples discussed in these chapters are ones that people encounter in reading newspapers and magazines; they are important for understanding the impact of science on modern thought and technology.

In the later chapters of the text, I emphasize the relationship between the structures of materials and their physical and chemical properties. The chemical structures of silicates and clays are related to the properties of glass and ceramics. The ion exchange properties of soils are presented along with the production of chemical fertilizers. The history of the introduction of copper, iron, and aluminum is related to differences in the chemistry of these metals and their compounds. Petroleum and gasoline, structure-property relationships for soaps, detergents and membranes, and environmental issues surrounding the use of halogenated hydrocarbons are used to illustrate some of the chemistry of organic compounds. Structure property relationships of synthetic polymers illustrate the way that scientists can design molecules with a wide variety of desired properties. A discussion of the important biochemical polymers provides a background for understanding the growing field of genetic engineering.

■ Special Chapters

Two chapters in the text focus on topics important for the consideration of technology and the environment and for science and society. In chapter 7, a consideration of the interaction of radiant energy with matter leads to a consideration of the environmental threats posed by the depletion of the ozone layer and by global warming. In chapter 12, problems associated with the growth of the use of energy and with extensive reliance on petroleum, coal, or nuclear energy are discussed.

■ Asides

Asides are an important feature of this text. They are used to enrich the reading, for subsequent material does not build on them. The asides go beyond the material under discussion in a variety of directions. They may present additional history, an aspect of the philosophy of science, an application to another scientific discipline, or a short exploration deeper into the topic at hand.

Reflections

Reflections are a novel feature of this text. In the reflections, I offer short essays that attempt to place concepts encountered in chemistry in a wider societal context. I may raise more questions than I offer answers. If the reflections provoke thought and promote a dialogue between student and student or student and instructor, they will have served their purpose well.

Questions

Questions are an important part of any chemistry text. Many of the questions in this text ask the student to think about an experiment or an application of chemistry. Students enjoy discovering that they too can understand experiments and can appreciate the scientific basis of some of their everyday experiences. Many of the questions are open ended and are addressed particularly to non-science majors.

Acknowledgments

I am grateful for the suggestions and support from students and colleagues at Sewanee. I appreciate the many students who have enrolled in Chemistry 100, a course taken to satisfy part of the math/science requirement. Their interest and occasional enthusiasm have been of great help in bringing this book to completion.

I appreciate the encouragement and contributions of people at William C. Brown. They have been supportive of the thrust of the book, and they have been committed to producing a quality textbook at an affordable price. Reviewers of this book have offered thoughtful criticisms and many detailed suggestions for improvements. They helped make this a better book. They are

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CHAPTER

1

From the Beginnings of Modern Chemistry to Dalton's Atomic Theory

Chemistry is a science that deals with everyday substances: the gases of the air, the rocks and soil of the earth, and the waters of the rivers and seas. Chemistry treats transformations of matter such as those occurring in the combustion of fuels, the smelting of metals, and the cooking of foods. The vocabulary of chemistry is familiar and pervasive. People eat fruits that are acidic and vegetables that are good sources of vitamins. They wash their hair with shampoos which may or may not be pH balanced. They wear rings of gold and clothing of natural fibers or they wear silver with polyester.

Chemistry played an essential role in the emergence of the modern world. The ability to make high quality steel made possible the machinery and transportation improvements that were the heart of the industrial revolution. The technology to produce strong, lightweight aluminum ushered in the age of flight. Fertilizers made agriculture more productive, and synthetic polymers replaced wool and cotton to help clothe growing populations. New drugs conquered many age-old diseases and ushered in the era of modern medicine. New explosives made war more terrible and yet helped to build dams that insured adequate water for cities and farms.

With the benefits of modern technologies come new and formidable problems. What do we do with our wastes? How do we provide clean water to drink and clean air to breathe? How long can we prolong life without answering questions about the quality of life? Chemistry offers insight into both the achievements of modern industry and the environmental issues that now confront society. It is a science that can be used to help provide enlightened responses to the problems we face.

Chemistry is the study of the composition and transformations of matter. Chemists seek to understand the structure of materials and the changes that occur when one material is converted to another. The development of chemistry as a science shows how people gained an understanding of the composition of matter and its changes. Even though chemical change has always been a part of human experience, the emergence of modern chemistry as a science is a recent development. During the period of 1750–1815, individuals performed experiments that led to discoveries of regular patterns in nature. Efforts to explain regularities in nature gave rise to the atomic theory that is basic to modern chemistry.

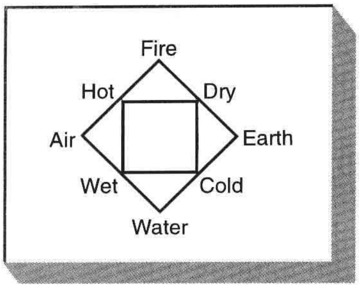

Figure 1.1
Early Greek ideas about matter emphasized properties of substances. For example, the element earth was thought to be dry and cold. The properties of real materials were thought to reflect the presence and properties of the elements earth, air, water, and fire.

■ Antecedents of Chemistry

The idea that all matter was composed of a small number of *elements* first arose in Greece. Greek philosophers considered air, earth, fire, and water to be the four elements from which all other substances were made. Elements endowed substances with properties: hot or cold, wet or dry, light or heavy (see Fig. 1.1). For example, a metal obtained by heating an ore was considered a compound of the elements earth and fire. It had substance due to the presence of earth, and it was shiny because it contained fire. Changes in materials were explained by changes in the quantities of the four elements within the compound. This viewpoint was a forerunner for the development of scientific ideas, as explanations were tested against observations.

The name, chemistry, is derived from *alchemy* which describes a wide variety of ideas and practices, over several centuries, and in many countries. Alchemy originated in Alexandrian Egypt. It flourished in the Arabic world and entered Europe through Moorish Spain. Its origins included both practical technology utilized by artisans and speculations about elemental nature as devised by the Greeks.

One aim of alchemy was *transmutation,* the effort to turn base metals such as iron into gold. From a modern chemical standpoint such an effort is doomed to failure, but to some alchemists it made sense. Gold was considered to be the noblest and most incorruptible of metals. According to Islamic records from the tenth century, the following doctrine formed a basis for attempting to transmute gold. Just as health is the state of perfection for the body, gold is the state of perfection for metals. Metals strive for the essence of goldness. In practice, alchemists sought to remove that which was imperfect and to add that which was lacking to attain perfection. At some times and in some places, alchemy also included recipes for making cheaper metals, such as silver, appear as gold.

Alchemists made important discoveries in the areas of early metallurgy and pharmacology. They extracted plant materials and they purified volatile materials by distillation. In the course of their work they developed recipes for the production of some acids and bases used in the investigations that established modern chemistry. Among the materials first described by alchemists are phosphorus, arsenic, antimony, bismuth, and zinc, all elements in the modern sense. Both apparatus and vocabulary in chemistry have been passed down from alchemy, and alchemy provided a crude framework of explanations for natural phenomena.

Unfortunately, competing and often confusing explanations for chemical changes abounded. Alchemy was, at times, forbidden by civil or religious authorities and practiced as a secret art. Its vocabulary was obscure, and its symbols carried both chemical and mystical meanings. For modern chemistry to develop, it was necessary to sort the natural explanations for chemical changes from the mystical interpretations of those changes.

■ Setting the Stage—Questions Facing Early Chemists

What are the properties of a substance? Is a given substance pure or is it a mixture? These are not trivial questions, and their answers were slow in coming. For example, even the description of something as familiar as water poses problems. Samples of water differ, for instance, sea water tastes salty, some spring water bubbles, and other spring water smells foul and tastes bad. How can one know if water is pure? Which properties of a sample of water are due to impurities and which are the properties of water itself?

If the analysis of water poses problems, consider the greater problems posed by a metal such as copper. Early samples of metals usually contained contaminants from the ore, and ores mined in different places often contained different impurities. Which sample of copper might be purer? How would one decide?

Greek philosophers, alchemists, and early chemists sought to explain chemical change in terms of elements and compounds. But what are elements? And what are compounds? Some substances had been observed in a wide variety of chemical reactions. For example, copper was obtained from a variety of ores, and sulfur (brimstone) reacted with most metals. One philosopher argued for a two element theory of matter based on copper and sulfur. Are copper and sulfur elements, or are fire and earth? The problem was how to decide whether a given substance was an element, a compound, or a mixture.

In asking these questions, a scientific attitude is implied, an attitude not found among educated people in the Middle Ages. Medieval Western attitudes were influenced by the Greek philosopher Plato. According to Plato's philosophy, real things were imperfect representations of the ideal just as circles drawn in the sand are imperfect representations of the ideal circle. When the goal of study is to understand the ideal or essence, experimental knowledge is of lesser value. The early chemist's decision to study the particular properties of particular samples of materials by observation represented an important change in people's thought.

■ The Beginnings of Modern Chemistry

The philosopher Francis Bacon (1561–1626) set forth a program for experimental science, calling for the direct observation of nature. In his preface to *True Directions Concerning the Interpretation of Nature,* he wrote:

> Those who have taken upon them to lay down the law of nature as a thing already searched out and understood . . . have therein done philosophy and the sciences great injury. For as they have been successful in inducing belief, so they have been effective in quenching and stopping inquiry; and have done more harm by spoiling other men's efforts than good by their own.

In 1661, Robert Boyle (1627–1691) published *The Skeptical Chemist.* Boyle wrote that elements were:

> certain primitive and simple, or perfectly unmingled bodies; which not being made of any other bodies, or of one another, are the ingredients of which all those called perfectly mixt bodies are immediately compounded, and into which they are ultimately resolved.

Boyle criticized Greek ideas concerning a four-element explanation of matter, and he critically examined and rejected some of the claims of alchemy. Boyle's definition set the stage for the further evolution of ideas concerning elements and compounds, but it failed to indicate how one could decide if a particular substance was an element.

To find better explanations, additional and careful observations were required. Those qualities most useful for the characterization of substances had to be identified, and ways to prove or disprove the interpretations of chemical changes needed to be found. In this process, there was a shift from qualitative observations to quantitative measurements. The qualities "hot" and "cold" were replaced by thermometer readings; "light" and "heavy" by balance readings. Modern chemistry began with discoveries that disproved plausible explanations of natural phenomena based on

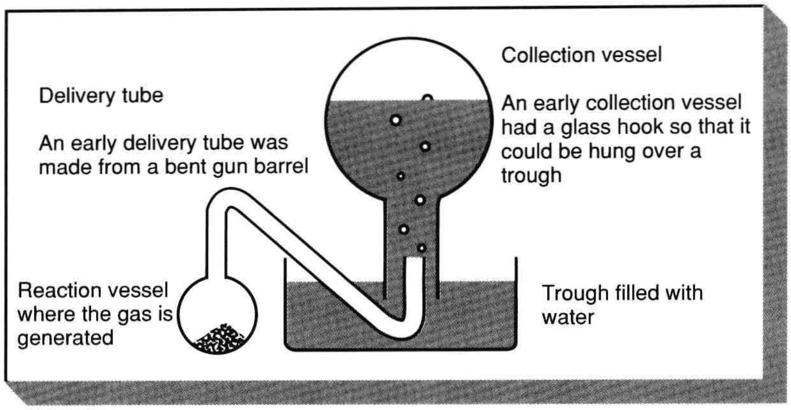

Figure 1.2
Early scientists collected gases by the displacement of water from an inverted container.

four elements. Air was shown to be a mixture, and water, a compound. We will examine the intimate relation of these experimental observations to the development of chemical explanations.

■ The Study of Gases

During the period from 1760 to 1780, scientists prepared, collected, and described a number of pure gases. This work contributed to the development of a new understanding of the nature of gases. Gases were collected by the displacement of water (Highly water soluble gases were collected over mercury.) from an inverted container as shown in figure 1.2. Properties of each gas were studied—Did it burn? Did it support the combustion of a candle? Did it dissolve in water? Similarities and differences of the collected gases were catalogued.

Because a gas separates from the liquid or solid from which it is generated, gases prepared by synthesis were generally very pure. This is important since one can conclude that the properties of these gases were not altered by the presence of impurities.

Acids and bases, substances that were known to the alchemists, were used to produce some gases. *Acids* taste sour, fizz with soda, and cause some vegetable dyes to change color. *Bases* taste bitter and reverse the color changes caused by acids. For the following studies concerning the generation and testing of gases we need to know two acids and one base. The common acids are *sulfuric acid,* prepared by heating an iron salt (hydrated ferrous sulfate), and *hydrochloric acid,* prepared by adding sulfuric acid to common salt and distilling a gas into water. The common base is *quicklime,* produced by heating limestone.

■ Air and Combustion

Early scientists were interested in combustion, for it was fire that brought about chemical change. Air would support the burning of a candle or the respiration of a mouse under a bell jar. When the flame went out or the mouse died, the remaining "air" had different properties. A part of this gas called "fixed air" readily dissolved in limewater (a solution of base made by dissolving quicklime in water) to produce a white precipitate (A *precipitate* is a solid formed by a reaction occurring in solution.). Another part, the "noxious air" remaining after the fixed air was dissolved in base, did not support combustion or respiration (see Fig. 1.3).

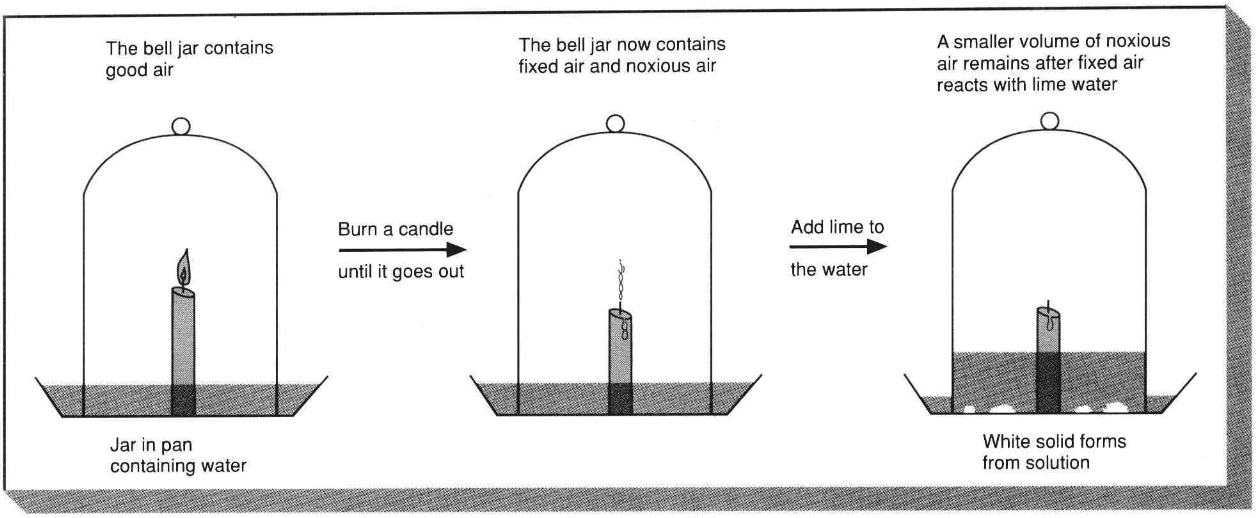

Figure 1.3
In the eighteenth century, scientists studied the changes in air that accompanied the burning of a candle. In the course of their studies, they prepared fixed air now known as carbon dioxide and noxious air now known as nitrogen.

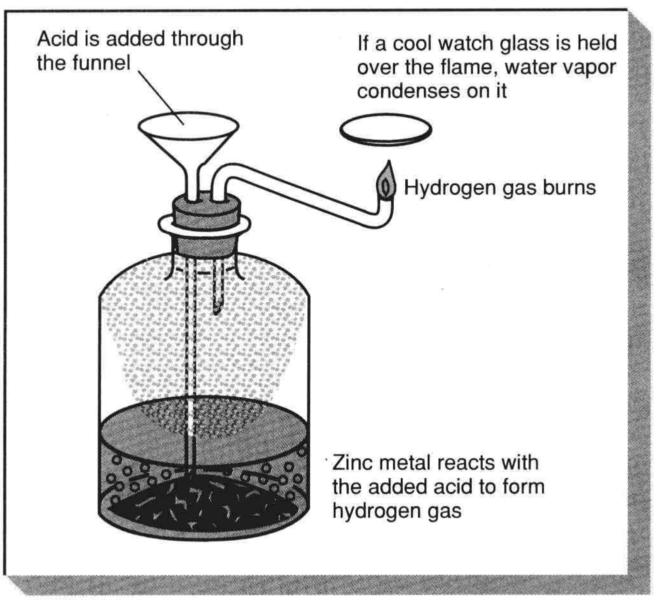

Figure 1.4
Hydrogen gas is produced by the reaction of zinc metal with dilute sulfuric acid. Water is produced when the hydrogen gas burns in air.

The fixed air produced by combustion and the noxious air remaining after combustion were two of the first gases to be described and characterized. Fixed air, now known as *carbon dioxide,* was produced by respiration or combustion. It could be prepared in a pure form and studied by adding acid to the white precipitate formed by the reaction of carbon dioxide with limewater. Noxious air, now known as *nitrogen,* remained after the carbon dioxide was dissolved in base.

Early scientists also produced "inflammable air" or hydrogen, by the action of sulfuric acid or hydrochloric acid on zinc or iron. Hydrogen gas burns in air, and by condensing the vapor above the flame on a cold surface, it was seen that water is produced by the burning of hydrogen (see Fig. 1.4).

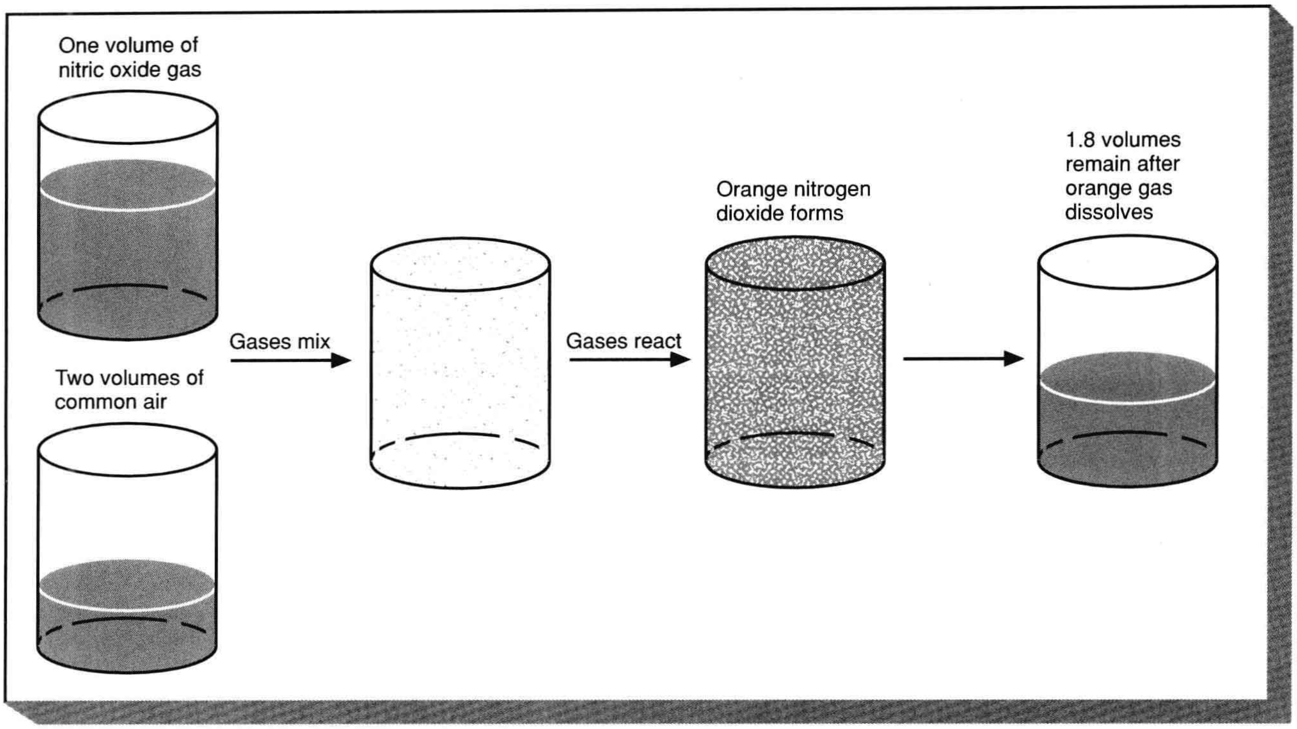

Figure 1.5
Joseph Priestley devised a test for the goodness of air that involved the reaction of air with nitric oxide. A larger final volume of gas remained if the air had been spoiled by burning or breathing.

■ Joseph Priestley Discovers Oxygen

Joseph Priestley (1733–1804) prepared and described a number of previously unknown gases. In the course of his investigations, he developed a chemical test for the "goodness" of air, that is, its ability to support respiration. (Modern names rather than the names given by Priestley are used to describe his test.) When 2.0 L of common air was mixed with 1.0 L of nitric oxide over water, orange fumes formed and the volume decreased to 1.8 L as the orange gas dissolved (see Fig. 1.5). The remaining gas, being mostly nitrogen, would not support combustion. If the common air had been spoiled by breathing or burning, a larger final volume of gas remained.

Priestley used this test in experiments that led to the discovery of oxygen. He found that heating an orange solid known as mercury calx produced liquid mercury and a gas, which he collected and studied. Priestley found that glowing charcoal placed in the gas burst into flame. One day he tested the gas for its goodness as air by mixing two volumes of the gas with one volume of nitric oxide. Orange nitrogen dioxide formed and then dissolved in water. The next day, he happened to put a glowing candle in the gas remaining after the test. The candle burst into flame. Unlike common air, all of the gas obtained by heating the mercury calx would support combustion.

Priestley had discovered oxygen. The mercury calx that Priestley heated is now known to be mercury oxide. Priestley had decomposed mercury oxide into mercury and oxygen.

$$\text{mercury oxide} \rightarrow \text{mercury} + \text{oxygen}$$

Priestley's test for the goodness of air can now be interpreted; nitric oxide reacts with oxygen in the air to form orange nitrogen dioxide.

$$\text{nitric oxide} + \text{oxygen} \rightarrow \text{nitrogen dioxide}$$