CHAPTER 3

The Chemical Revolution

CHEMISTRY OFTEN GETS treated as the poor relation in histories of science. Traditionally, historians of science have had a great deal to say about major developments in the physical sciences during and since the Scientific Revolution. Similarly, a great deal of historical attention has been devoted to the life sciences, particularly in the context of Darwinism, its origins, and its consequences. Developments in the chemical sciences, by contrast, have been regarded as rather less earth shaking in their consequences. There are a number of possible reasons for this comparative neglect. Historically, many of the practices and ideas that we might now characterize as chemical originated in a wide variety of different contexts and places. Alchemists, apothecaries, doctors, dyers, and metalworkers all engaged in activities that we might now think of as having to do with the origins of chemistry. Faced with this wide variety of origins, historians of chemistry have sometimes found it difficult to come up with a unified view of the science's development. In other words, it is quite difficult to extend a coherent and contained discipline of chemistry very far back into the past. Another problem has to do with the perception of chemistry as a practical rather than a theoretical science. Until comparatively recently, historians of science have regarded themselves as historians of ideas. From this perspective, practical sciences such as chemistry have often simply seemed less worthy of historical attention. Physics and biology have had their big philosophical ideas. There seem to be no clear equivalents in the history of chemistry.

The traditional view has been that chemistry did not play a major role in the so-called Scientific Revolution of the sixteenth and seventeenth centuries. On the contrary, according to at least one historian, chemistry was behind the times by almost a century (Butterfield 1949). According to this view it was only at the end of the eighteenth century that the "delayed Scientific Revolution in chemistry" eventually took place. Before the French chemist Antoine-Laurent Lavoisier's systematic reform of chemical ideas and language and the overturning of the phlogiston theory in the closing decades of the eighteenth century, chemistry remained in a kind of scientific Dark Ages. While physics (or, more properly, natural philosophy) had embraced the Newtonian ideal of a rigorously quantitative and experimental methodology, chemistry remained wedded to woefully vague and qualitative approaches. More recent historians recognize that this view of chemistry before Lavoisier begs several questions. As we have seen already, few historians would now agree with the idea that there was a uniquely scientific revolution during the sixteenth and seventeenth centuries, still less that it resulted in a uniquely defined scientific method (see chap. 2, "The Scientific Revolution"). In much the same way, historians of chemistry are now far less likely to regard Lavoisier's contributions in themselves as having decisively inaugurated a new era (Ihde 1964).

In that respect we need to think quite carefully about the proposition that there was a chemical revolution at the end of the eighteenth century. As in the case of the Scientific Revolution more generally, it is important to recognize just what is being argued. To accept the case for regarding the changes in chemical theories and practices that took place during this period as constituting a uniquely defined chemical revolution in the sense that Butterfield, for example, had in mind, we would need to accept that the chemistry that emerged from the end of the eighteenth century was in some way recognizably modern in a way that previous chemistry was not. We would also need to accept that this transformation was unique. Historians are now far more aware of the range and complexity of chemical theories and practices before Lavoisier and the important contributions that earlier chemists made. It is also clear that the debates surrounding chemistry at the end of the eighteenth century can no longer be regarded plausibly as a straightforward battle between enlightened supporters of Lavoisier's chemical reforms, on the one hand, and blinkered rejectionists on the other. In reality the range of positions was far more complex. Neither were Lavoisier's reforms as decisive as they were once considered to be. Many aspects of Lavoisier's theories would appear as peculiar to modern chemists as those of his predecessors and adversaries.

We will commence this chapter with an overview of "unreformed" chemistry during the seventeenth and early eighteenth centuries — or, more accurately perhaps, a survey of some of the practices and activities that later came to be called chemical. It should become clear that regardless of the views of later generations of chemists and historians of chemistry, chemical practitioners such as Robert Boyle, Paracelsus, and Georg Stahl regarded themselves as fully committed to the New Science. We will then look at the development of pneumatic chemistry during the eighteenth century, particularly the work of English chemist and natural philosopher Joseph Priestley. Looking at Priestley's contributions will help to make clear the role chemistry played in eighteenth-century science and culture and the wider ramifications of phlogiston theory. Against this background we will then examine Lavoisier's contribution to chemistry, in particular his rejection of phlogiston theory in favor of his own theory of oxygen and his efforts to establish a new, reformed chemical language. We will see how Lavoisier's chemical innovations can be located within the particular context of late eighteenth-century developments in French chemistry and natural philosophy (and French intellectual and political culture more generally). Finally, we will look at developments in chemistry in the immediate aftermath of Lavoisier's innovations during the opening decades of the nineteenth century. We will look at Humphry Davy's flamboyant electrochemical experiments, John Dalton's development of atomic theory, and Jöns Jacob Berzelius's development of an electrochemical theory of the elements based on his own and Davy's experiments. This will help to make clear the extent to which his immediate chemical successors regarded Lavoisier's innovations as decisive and the extent to which they regarded his theories as providing only one of a number of possible approaches to reforming chemistry.

Chemistry Unreformed?

Many practitioners engaged in activities we might now characterize as "chemical" certainly regarded themselves as being at the forefront of the New Science during the sixteenth and seventeenth centuries. Alchemists such as Michael Sendivogus or even Sir Isaac Newton viewed themselves as the inheritors of a tradition stretching back into antiquity. The aim of their science was to understand the hidden relationship between natural substances and to find the key that would allow the transmutation of one element into another. Apothecaries and doctors were interested in the medicinal properties of substances. Medical reformers like Paracelsus and Joan-Baptista van Helmont wanted to develop new theories of matter that would lead to new understandings of the medical applications of natural substances. Metallurgists such as Vannoccio Biringuccio developed and tabulated new recipes for the improved production of metals as well as other industrial products such as dyes and gunpowder. Early eighteenth-century phlogiston theorists such as Georg Ernst Stahl were trained in this metallurgical tradition. The mechanical philosopher Robert Boyle carried out chemical experiments as a way of trying to understand the fundamental mechanical properties of matter—and he did not draw any sharp distinction between his chemical and other experimental activities. As we have seen already, far from regarding Boyle as working in an unreformed and antiquated tradition, many of his contemporaries considered him to be the archetypal new natural philosopher (see chap. 2, "The Scientific Revolution"). Other chemical practitioners were equally convinced of the novelty and importance of their activities (Debus 1987).

Renaissance and early modern alchemists worked in a tradition that stretched back to the Greeks (Newman 2004). Greek alchemists had tried to understand the methods involved in industrial processes such as metalworking and pigment making in terms of ideas about the fundamental elements of matter. Their medieval Islamic inheritors such as (the possibly mythical) Jabir ibn Hayyan and Al-Razi developed these ideas to form an extensive corpus of alchemical writings that were later borrowed in the Latin West. Early modern alchemists such as Michael Sendivogus, alchemist to the Holy Roman Emperor Rudolph II, claimed to be able to transmute elements into one another and to have particular mystic insights into the operations of nature. The Holy Grail of alchemy was the search for the philosopher's stone that was the key to the transmutation of one metal to another. Finding the stone would deliver not only limitless wealth (through the ability to transmute base metals into gold) but ultimate understanding of the secret nature of matter as well. Sendivogus was read by, among others, Sir Isaac Newton who investigated alchemy as part of his grand scheme to recover systematically the lost knowledge of the ancients. Alchemists developed a range of techniques and equipment designed to investigate the properties of different substances. They also developed an

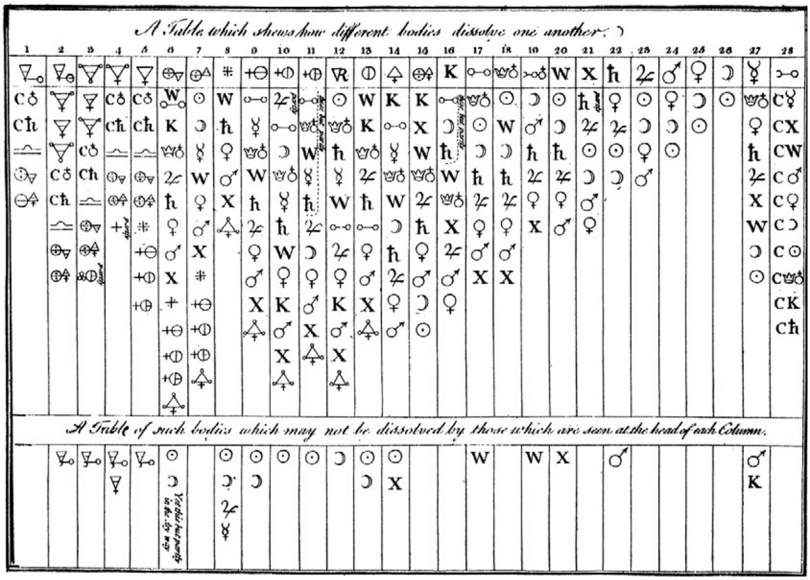

Fig. 3.1. A table of alchemical symbols from G. E. Gellert, *Metallurgic Chemistry* (1776).

arcane language and symbolism to hide their knowledge of such matters from the uninitiated (fig. 3.1).

Alchemical tracts such as (the fictitious) Basil Valentine's *Triumphant Chariot of Antimony* (1604) emphasized the medicinal properties of substances. This was the main concern of apothecaries and doctors investigating the properties of matter. The medical reformer Paracelsus (full name: Theophrastus Phillippus Aureolus Bombastus von Hohenheim—you can see why he changed it) were adamant that a new understanding of the ultimate properties of matter was a prerequisite of a reformed medicine. Like many another proponent of the New Science, Paracelsus had nothing but contempt for his predecessors in medicine such as the Alexandrian medical authority Galen. He chose his new name (Para-Celsus) to symbolize his superiority over the past in the form of the Roman medical writer Aulus Cornelius Celsus, author of *De medicina*. The aim of medicine was to prepare *arcana*—remedies for disease based on the properties of natural substances. Paracelsus called his new practice iatrochemistry (from the Greek *iatro*, meaning doctor). The task of the iatrochemist was to use the doctrine of signatures—the knowledge of the relationship between earthly bodies and astral essences—in order to identify what substances could be used to cure particular diseases. Substances were made up of the four elements (air, earth, fire, water) combined with the *tria prima* (three principles) of salt, sulfur, and mercury (or body, soul, and spirit). Like alchemists, Paracelsus argued that knowledge like this could only be made available to the initiated adept (Debus 1977).

Some iatrochemists, while applauding their master's insistence that chemistry was the foundation of proper medicine, abandoned some of Paracelsus's broader cosmological principles such as the doctrine of signatures and the *tria prima*. Jan Baptist van Helmont, a Flemish nobleman and follower of Paracelsus, denied the existence of the four elements and the *tria prima*. He held that there was only one element—water—along with the modifying principle of fermentation. Van Helmont demonstrated his claim in a famous experiment in which he grew a willow tree in two hundred pounds of dried earth regularly nourished with distilled rainwater. After five years the tree had grown in weight from 5 to 169 pounds while the weight of the earth remained the same. From this, van Helmont concluded that the increase in size of the tree had been entirely due to the added water. Like many iatrochemists, van Helmont was interested in the chemistry of physiological processes such as digestion, which he interpreted as a fermentation process. His followers such as Franciscus Silvius expanded the theory to explain digestion in terms of conflict between opposite principles of salts and acids. Van Helmont was a pantheist who denied any distinction between matter and spirit. Like Paracelsus he also regarded chemical knowledge as the particular preserve of the initiated few (Pagel 1982).

Helmontianism was popular in England during the first half of the seventeenth century, but following the Civil War and the Commonwealth its mystical aspects and overtones of personal revelation started to bring it under suspicion. A new generation of chemists like Robert Boyle turned to the mechanical philosophy rather than van Helmont's or Paracelsus's politically dangerous pantheism as a source of chemical explanation. Boyle's *Sceptical Chymist* (1661) dismissed Aristotelian, Paracelsian, and Helmontian theories of matter in favor of a corpuscular perspective. According to Boyle everything was made up of matter in motion. Rather than trying to explain the particular chemical and physical properties of substances in terms of the innate qualities of the various elements, Boyle argued that they should be seen as resulting from the particular shapes and arrangements of the corpuscles (or particles) making up those substances. One of Boyle's aims in embracing the mechanical philosophy as an explanation for chemical phenomena was to bring them within the ambit of natural philosophy. He wanted to do away with the arcane mysticism of Paracelsian or Helmontian approaches to chemical experiments, with their overtones of charlatanry, and make them into an activity in which gentlemen could take part without suspicion. He extolled the benefits in terms of medicine and the arts of a properly philosophical approach to the nature of matter (Kargon 1966; Thackray 1970).

Chemical practices were increasingly recognized as a useful source of new knowledge in the development of metallurgical and other industrial processes. In his *Pirotechnica* (1540) the sixteenth-century Italian engineer Vannoccio Biringuccio provided detailed recipes of metallurgical processes and the manufacture of industrially and militarily useful substances such as gunpowder. Chemical knowledge could be put to work in improving the purification of metals from their ores and in the production of alloys. Chemical skills and know-how were needed to improve the production of dyes and pigments for the cloth industries. Johann Becher's chemical investigations into the origins of minerals in the earth were an explicit effort to find new ways of exploiting such resources for economic gain. His *Physica subterranea* (1667) argued that minerals were made up of three types of earth—*terra fluida* (mercurous earth), *terra pinguis* (fatty earth), and *terra lapidea* (vitreous earth)—that defined their various properties. Becher's work was taken up by Georg Ernst Stahl, professor of medicine at the University of Halle, in the early eighteenth century as he developed his theory of phlogiston as a way of explaining metallurgical processes. He renamed Becher's *terra pinguis* as "phlogiston" and identified it as the principle of combustion in the production of metals from their ores. According to Stahl's theory, pure metals were the result of the combination of metal ores (or calxes) with phlogiston during the heating process (Brock 1992).

There seems little doubt that most if not all of these sixteenth- and seventeenth-century chemical practitioners would have regarded themselves as fully fledged participants in the production of the New Science. Even alchemists working in what they at least regarded as age-old traditions viewed what they were doing as an important contribution to contemporary knowledge. Newton, for example, was interested in alchemy precisely because it offered a path to recovering lost knowledge in just the same way as he regarded his universal theory of gravitation as doing. To seventeenth-century eyes there was no contradiction between investigating ancient systems of knowledge and discovering new ones. Paracelsus and van Helmont, while deeply steeped in alchemical lore, also regarded what they were doing as a radical break from past practice. Like other proponents of the New Science, such as Galileo and Boyle, chemists also promoted the utilitarian aspects of their practices. Their activities could contribute to improving the manufacturing arts and the wealth of nations. Becher, for example, was a cameralist—an advocate of the systematic intervention of the state to support commerce and manufacturing industry. His research into the theory of mineral production, carried out under the patronage of the Holy Roman Emperor Leopold I was quite straightforwardly part of his efforts to improve mining technology for the benefit of the state. If the defining feature of the Scientific Revolution is taken to be its participants' efforts to reform and reorganize knowledge then by their lights, at least, chemists were active participants in those efforts. Nevertheless, it is arguable that only in retrospect can the range of activities and practices we have discussed here really be described as chemistry, in the sense of a coherent and contained discipline.

Pneumatic Chemistry

Joseph Wright of Derby's famous painting *An Experiment on a Bird in the Air-Pump* (fig. 3.2) painted in 1768 captures the increasingly important role of chemical investigations in eighteenth-century science and culture very well. In particular it highlights the central role played by investigations into the chemistry of gases—pneumatic chemistry, as it was called. Before the eighteenth century, the air was usually taken to be a single substance, one of the four Aristotelian elements. Eighteenth-century chemists, however, started to discover different kinds of air, with a variety of chemical properties and effects. Wright's painting shows a chemist demonstrating the properties of one of these new airs by showing whether a bird could survive breathing it. The chemist is demonstrating the experiment to a group of well-dressed middle-class witnesses. The newly prosperous middle class was an important new audience for science during the eighteenth century. They were attracted by its utility and the lessons that might be learned by studying the order of nature. In the hands of radical natural philosophers and chemists such as Joseph Priestley even the chemistry of gases could be shown to carry important political messages. It was also a source of new technologies and played a key role in transforming the language of chemistry at the end of the century.

Investigating the chemical properties of the air was an eighteenth-century innovation. Seventeenth-century chemists usually assumed that air was chemically inert and therefore played no role in chemical reactions. The English clergyman and natural philosopher Stephen Hales, known for

Fig. 3.2. Joseph Wright's *Experiment on a Bird in an Airpump* (1768). A chemist demonstrates his experiments to a group of fashionable onlookers. The painting illustrates the increasing cultural importance of chemistry and natural philosophy during the eighteenth century. Courtesy of the National Gallery, London.

his investigations into the natural philosophy of plants (*Vegetable Staticks*) and animals (*Haemostaticks*), was one of the first to suggest that the air was chemically active. He had started investigating the air on discovering, during the course of experiments on plants, that large quantities of air were "fixed" in solid matter and could be released by heating. The instrument he developed to collect this air—later developed by the English doctor William Brownrigg into the pneumatic trough—was a key tool for chemical investigation throughout the rest of the century. Air produced by heating was washed of impurities by being passed through water before being collected in an inverted jar. Hales's observation that air could combine with other forms of matter focused chemists' attention. His discovery was pursued further by the Scottish chemist Joseph Black, among others. Black found that by heating the substance *magnesia alba* (a form of magnesium carbonate) he could produce a kind of air with distinct properties, which he called "fixed air"—what we would call carbon dioxide. He developed new ways of testing the air and determining its chemical properties through studying its reactions with acids and alkalis (Schofield 1970).

The key figure in eighteenth-century pneumatic chemistry was the English chemist, dissenting minister, natural philosopher, and political radical Joseph Priestley. The breadth of Priestley's activities captures well the broader context of chemistry during this period (Anderson and Lawrence 1987). Born to a religiously nonconformist family in the English Midlands, Priestley trained as a minister in a dissenting academy and served as minister to a number of congregations before being appointed as a tutor at Warrington Academy in 1761. While there he established links with leading religious radicals such as the Welshman Richard Price and befriended, among others, the soon-to-be American revolutionary, Benjamin Franklin. He established his reputation as a natural philosopher in 1767 with his *History and Present State of Electricity* and made his name as a chemist with *Experiments and Observations on Different Kinds of Air* in 1774. Picking up on Hales's and Black's observations, Priestley established the existence of a number of distinct kinds of air, each with specific properties. The two best known of these discoveries were nitrous air (now known as nitrous oxide or laughing gas) and dephlogisticated air (oxygen). In 1780 Priestley took up the ministry of the New Meeting House in Birmingham and while there joined the Lunar Society of natural philosophical enthusiasts including the industrialists James Watt and Josiah Wedgwood and the radical doctor and proponent of evolution Erasmus Darwin (Schofield 1963; Uglow 2002).

Priestley used his chemical discoveries as the foundations of a whole new philosophy of nature. To explain the different chemical properties of the different kinds of air he had established he turned to Stahl's theory of phlogiston. Different kinds of air had a range of chemical properties depending on the quantities of phlogiston they contained. Some airs, like Black's fixed air, contained relatively large amounts of phlogiston, others less. For a time Priestley assumed that normal atmospheric air was the air that contained the least phlogiston until he made a spectacular discovery in 1774. He found that by heating red calx of mercury he could produce an air that seemed to contain little or no phlogiston at all. According to Priestley's view of the "aerial economy"—the role different airs played in the natural order—this new dephlogisticated air was the best kind of air possible. Priestley argued that phlogiston, the principle of combustion (and corruption) was at the heart of the natural economy. Some processes, such as combustion, respiration, and the decomposition of animal bodies, released phlogiston into the atmosphere. Other processes, such as the actions of plants or the movement of water, removed it, thus maintaining a natural equilibrium. The best kinds of airs for human life were those that contained the least phlogiston. The newly discovered dephlogisticated air was therefore the most virtuous (Golinski 1992).

Priestley regarded this aerial economy as proof of divine benevolence. It showed the natural mechanism through which God kept the cosmos in a state of equilibrium. Everything in nature—plants, animals, the movements of wind and water, thunderstorms, earthquakes, and even volcanic eruptions—had a role to play in maintaining the economy of nature by adding to or subtracting from the amount of phlogiston in circulation. For a political and religious radical like Priestley, this view of nature's economy had important political and social consequences. Priestley famously claimed that "the English hierarchy, if there be anything unsound in its constitution, has reason to tremble even at an air-pump or an electrical machine." What he meant by this was that these scientific instruments helped reveal the proper order of nature. Since the social order should be based on this natural order and if, therefore, there was something wrong with the prevailing social order (and Priestley thought there was) scientific instruments could also be political instruments by showing how social injustices were at odds with nature. Priestley, as an outspoken political radical was an ardent supporter of both the American and French Revolutions. As a result of this support, his house and laboratory in Birmingham were burnt by a loyalist, "Church and King" mob in 1791, leading to his emigration to Pennsylvania in 1794 (Schofield 1970).

Priestley's pneumatic chemistry had other connotations as well, however. Some of his supporters, such as the Oxford professor of chemistry Thomas Beddoes—a student of the Scottish chemist Joseph Black—felt that Priestley's discoveries could provide the basis for a new system of medicine. As well as being an advocate of Priestley's views, Beddoes was a supporter of the medical theories of John Brown, who argued that health could be achieved by maintaining a proper balance of stimulants and sedatives in the body. Beddoes believed that the newly discovered airs could be used in this way (Jay 2009). Following his dismissal from Oxford for his radical political views, Beddoes established the Pneumatic Institute in Bristol in order to put his theories about the medical benefits of breathing different airs to practical use. He hired a promising young apothecary-surgeon's apprentice, Humphry Davy, to carry out experiments on the chemical and medicinal properties of the various kinds of air. Davy carried out a systematic program of chemical analysis on the airs, abandoning Priestley's phlogiston theory as he did so in favor of Lavoisier's new system of chemistry. His experiments on the physiological effects of breathing the

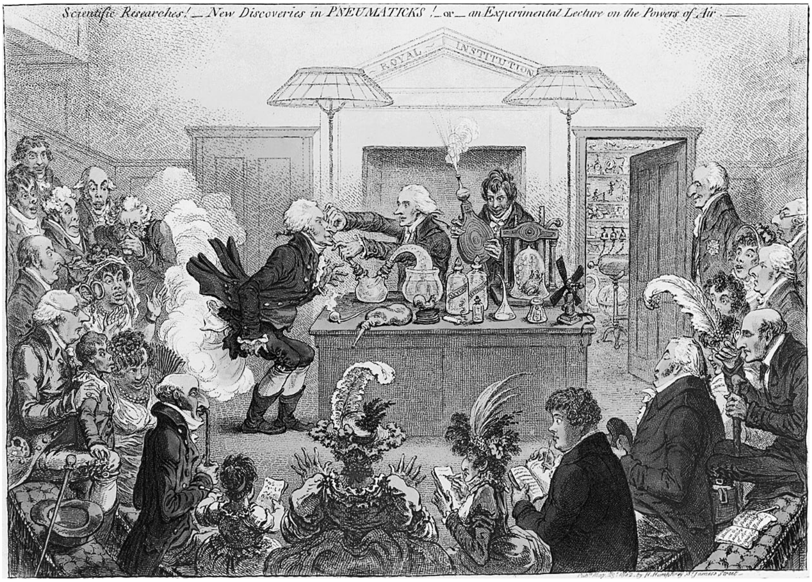

Fig. 3.3. *Scientific Researches!* by James Gillray. Pneumatic experiments at the Royal Institution, satirized. The institution's professor of chemistry, Thomas Garnett, is administering gas to a member of the audience. The man standing behind him wielding a bellows and wearing a satanic grin is Humphry Davy. The gentleman with a large nose on the far right, looking on benevolently, is the institution's founder, Count Rumford. NPG D13036; image courtesy of the National Portrait Gallery, London.

various airs—particularly nitrous oxide—made him both famous and notorious in late eighteenth-century England (fig. 3.3) and helped him secure the plum position of professor of chemistry at the newly established Royal Institution in 1803 (Fullmer 2000).

Beddoes's and Davy's efforts to put pneumatic chemistry to medical use remind us that there was more to phlogiston than simply a theoretical principle. It was also the basis of a practical chemical technology. Priestley had himself been one of the first to attempt the exploitation of pneumatic chemistry's medical potential when he patented a method of dissolving fixed air in water to produce the world's first artificially prepared fizzy drink. Priestley assumed that his artificial soda water would have the same medicinal qualities as the mineral waters drunk in gallons at spa resorts such as Bath or Malvern. He also developed an instrument that could measure the amount of phlogiston present in different kinds of air and thus assess its capacity to sustain animal and human life. The eudiometer worked by mixing the air to be tested in a glass tube with a quantity of nitrous air.

The extent to which the test sample changed in volume as the phlogiston in it combined with the nitrous air was a measure of the air's virtue. The science of eudiometry was particularly popular in industrial Britain where it was used to assess the quality of air in manufacturing districts and in Italy where the Milanese professor of experimental physics, Marsilio Landriani, devised an eudiometer he could use to demonstrate the effects of *mal aria* on his fellow citizens' health.

Priestley's example in particular shows how chemistry was at the very heart of the eighteenth-century Enlightenment. Far from being an example of a science that had somehow not yet caught up with the advances made in other areas, chemistry was widely recognized by many contemporaries as an example of just how important science could be to eighteenth-century society (Clark, Golinski, and Schaffer 1999). Chemists not only demonstrated that they were at the forefront of scientific progress as they saw it—developing powerful new theories and practical technologies—but that their science was making a major contribution to social progress too. It should also alert us to how careful historians of science ought to be in approaching past ideas that may now appear wrong or misguided. Some historians point to phlogiston theory—particularly the French chemist Guyton de Morveau's suggestion that phlogiston might have negative weight (since substances seemed to gain weight as they lost phlogiston during combustion)—as a prime example of how preconceived ideas can hold science back. This kind of "whiggish" approach is guilty of not taking past science seriously on its own terms and those of its practitioners. Phlogiston did not seem at all silly to its promoters such as Priestley—though, as it happens, few of them took de Morveau's suggestion seriously. Most argued that phlogiston was an immaterial principle and as such made no contribution to the weight of a substance one way or another.

Phlogiston versus Oxygène

One ongoing dispute in the history of chemistry involves the issue of who should be considered the discoverer of the gas oxygen. The historian and philosopher of science Thomas Kuhn uses the episode as a classic example of the difficulties involved in reconstructing the "historical structure of scientific discovery" (Kuhn 1977). In the case of the discovery of oxygen, we have three candidates for the status of discovery. The first is Carl Scheele, a Swedish chemist who during the early 1770s succeeded in isolating what he called "fire air" through a variety of methods. He did not announce his results publicly until much later, however. The second candidate is Joseph Priestley with his isolation of a new air in 1774 and his identification of it as dephlogisticated air in 1775. The final candidate is Antoine-Laurent Lavoisier, who repeated Priestley's experiments and redesignated the air as oxygen in 1776, using it as the cornerstone of his new system of chemistry. Kuhn wanted to make two points about discoveries using this example. In the first place, he pointed out that discoveries were not simple, straightforward events. They had a historical structure. He pointed out, for example, that it had taken time and several efforts at identification before anyone recognized oxygen for what it really was. Second, he pointed out that discoveries were only possible within the context of a theoretical system. Whether dephlogisticated air or oxygen gas had been discovered depended on whether Priestley's or Lavoisier's systems of chemistry were accepted.

Kuhn saw Lavoisier's new system of chemistry as an example of a scientific revolution. It was his recognition that this new substance was an anomaly that did not fit into established systems that led to his conceptual breakthrough and development of a new way of understanding chemical processes. Lavoisier, by the 1770s, was a highly respected French chemist and a member of the Académie Royale des Sciences. He came from a prosperous middle-class background and had originally been intended for a career in the law before taking up chemical studies at the Collège Mazarin. His teacher there, Guillaume-François Rouelle, was an exponent of Stahl's theory of phlogiston. By the mid-1760s Lavoisier was already making a name for himself in French philosophical circles as an ambitious young chemist. He was appointed to the lowest rank of the Academie des Sciences in 1768 and commenced on a career as a "scientific civil servant," putting his chemical expertise at the service of the French state (Brock 1992; Donovan 1996). Lavoisier was independently wealthy after his father made over a large inheritance to him. He used his wealth to buy shares in the Ferme Générale—a company that had acquired the rights to collect taxes on behalf of the state. It was his status as a shareholder in the Ferme that led to his execution by guillotine in 1794 in the aftermath of the French Revolution.

During the late 1760s Lavoisier was particularly interested in the chemistry of the air and the role it played in combustion and the isolation of metals from their ores (calxes). Phlogiston theorists argued that metals were a combination of a calx and phlogiston. During combustion, phlogiston from the fire combined with the calx to produce a metal. By about 1770 Lavoisier was convinced that the air must play some role in the reaction too. In 1772, on the basis of experiments carried out with the Academie des Sciences's

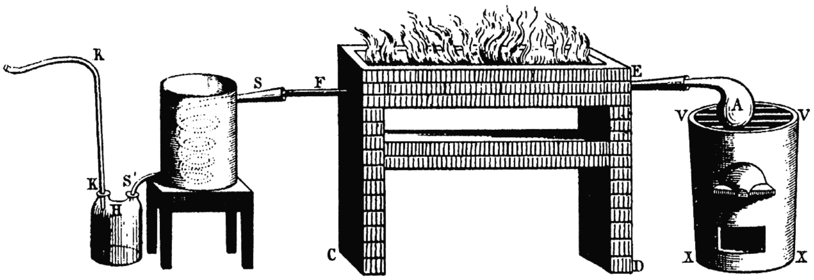

Fig. 3.4. An eighteenth-century chemical experiment showing the decomposition of steam by iron.

great burning lens, he suggested that gaseous air was in fact a combination of aerial matter and phlogiston (fig. 3.4). Heating metal in air thus led to the production of a calx (a combination of metal and aerial matter) and liberated phlogiston in the form of heat. On the basis of these and other experiments he deposited a sealed note at the Academie, laying claim to the hypothesis that the basic process taking place during combustion was the combination of the burning substance (like a metal) with aerial matter and that this accounted for the fact that substances increased in weight on combustion. By 1775, having come across Priestley's account of dephlogisticated air he refined his account further. He now argued that it was this dephlogisticated air, which he called *oxygène* that played the key role in combustion (Guerlac 1961).

In introducing *oxygène,* Lavoisier abandoned the phlogiston theory. In its place he offered a comprehensive new theory based around the new gas. The word "oxygen" came from the Greek, meaning "acid former" since Lavoisier had noticed that the substances formed by the combination of metals or carbon with this new principle were all acids. Oxygen gas, he argued, was composed of oxygen (the principle of acidity) and caloric (heat). During combustion, the principle of acidity combined with the metal to produce an acidic calx while the caloric from the gas was released in the form of heat. Lavoisier wanted his theory to do far more than explain the principles of metallic combustion, however. He wanted it to be the basis of a new and unified chemical system. One problem in this respect was the anomalous production of "inflammable air" when a metal was treated with an acid. This was easy to explain according to the phlogiston theory. The acid combined with the calx in the metal to produce a salt while releasing phlogiston as inflammable air. Lavoisier only solved this problem in the 1780s when the English chemist Henry Cavendish carried out experiments that seemed to show that water was a compound of dephlogisticated and inflammable air. Lavoisier could now argue that when metals combined with acids, the inflammable air came from the water in which the acid was dissolved. He called the gas hydrogen, meaning "water former."

One particularly important feature of Lavoisier's attempt to reform chemistry was the way in which he developed a whole new chemical language using his new theory. In 1782 Lavoisier, along with his French fellow chemists Guyton de Morveau, Claude-Louis Berthollet, and Antoine Fourcroy, published the *Méthode de nomenclature chimique* in which they described a new way of naming chemicals on the basis of the oxygen theory. All substances that could not be decomposed any further (like carbon, iron, or sulfur) were taken to be elements and formed the basis of the naming system. What had been called calxes were now called oxides, since they were the result of combining simple elements with oxygen, giving oxides of carbon, iron, or zinc, for example. Acids were named after their elements according to the amount of oxygen involved in their creation, as in sulfurous or sulfuric acids, respectively. As well as the metals and the bases of various salts along with hydrogen and oxygen, Lavoisier's list of elements also contained one other gas—azote (now called nitrogen). It also contained two other elements—caloric and light. The new system embodied Lavoisier's chemical theories. Simply by using it, chemists were signaling their acceptance of the oxygen theory around which it was based.

Lavoisier's reform of chemistry was widely recognized as radical and controversial. Some supporters of the phlogiston theory, notably Joseph Priestley, never accepted it. Another English chemist who remained convinced of the superiority of the theory of phlogiston was Henry Cavendish, despite the fact that his observations on inflammable air had formed one of the key factors in Lavoisier's reform. A number of English chemists were, however, converted to the oxygen theory within a comparatively short period. The rising star of late eighteenth-century English chemistry, Humphry Davy, was a supporter of Lavoisier's new chemical system, although as we shall see, he was soon to become one of its most committed opponents. In Scotland, by the 1790s the chemist Joseph Black was also teaching the new chemistry, and he along with his successors at Edinburgh introduced oxygen to new generations of medical students. In the German lands, opposition to the oxygen theory remained common until the early years of the nineteenth century. Yet even there, translations of Lavoisier's key works were being published by the early 1790s. In France, acceptance of the new theory was particularly rapid. Prominent supporters of the phlogiston theory such as Guyton de Morveau were quickly converted—even, as we have seen, collaborating with Lavoisier in spreading the new doctrine.

One reason that Lavoisier's chemical system succeeded so quickly in France was the way in which it fitted in with other contemporary developments in French science and philosophy. For a new generation of French natural philosophers, the keys to progress in science were quantification and accurate measurement. Natural philosophers such as the rising star Pierre-Simon Laplace were convinced that this was the only way to make sure that Newton's success in astronomy and mechanics could be repeated in other areas of physics. Lavoisier's emphasis on carefully weighing the ingredients and products of chemical reactions and his insistence that changes in weight provided the crucial evidence for what went on in such reactions fitted in well with this concern for quantification. In the same way, his efforts to reform the language of chemistry and his insistence on the need for a comprehensive system of chemistry chimed well with broader French philosophical concerns. Philosophers such as Denis Diderot and Jean le Rond d'Alembert argued that the whole of philosophy needed systematic reform. The philosopher Étienne Bonnot de Condillac argued that reforming language was an essential prerequisite of reforming the ways in which people thought. In many ways, therefore, it seemed to his French contemporaries that Lavoisier's reforms in chemistry were part of a bigger picture. They were part of a larger reordering of the French intellectual world (Holmes 1985).

Past historians of chemistry have regarded Lavoisier's rejection of phlogiston and his reform of the language of chemistry as decisive moments in the chemical revolution. Before Lavoisier, chemistry was stuck in the Dark Ages. After Lavoisier, it was a recognizably modern science. It is worth pausing briefly here to consider how accurate this view is. However familiar many of its central features may appear to us, such as the role of oxygen in combustion and the new nomenclature, many features of Lavoisier's chemistry should also appear quite strange. While he had banished phlogiston from his system, the immaterial principle of heat remained in the form of caloric. Neither was caloric the only immaterial principle that took its place in Lavoisier's table of elements. Lavoisier's identification of oxygen as the principle of acidity—which formed the linchpin of his system—has also long been abandoned by modern chemists. At the same time, there can be little question that the phlogiston theory that Lavoisier abandoned was itself a powerful and versatile theoretical tool. It might sound peculiar from a modern perspective, but in the hands of experienced practitioners such as Joseph Priestley or Henry Cavendish it provided highly sophisticated explanations of known chemical phenomena and of recent discoveries such as the new kinds of airs. In that respect, at least, there was nothing inevitable or self-evident about the success of Lavoisier's theory or about its status as the key to the revolution in chemistry.

Chemistry Reformed?

One way of assessing the significance of Lavoisier's revolution in chemistry is by looking at the state of chemical knowledge in the decades immediately following the introduction of his reforms. Was Lavoisier's new chemistry quickly and universally adopted? How long was it before Lavoisier's reforms were themselves reformed? Kuhn characterizes a scientific revolution as a period of massive intellectual change followed by a period of "normal science" during which the implications of new conceptual frameworks and theories are explored and articulated. Did a period of such "normal science" follow the revolution in chemistry? It seems relatively clear, as we have already seen, that Lavoisier's reforms were adopted comparatively quickly and comprehensively. By the beginning of the nineteenth century, there were very few chemists who were still fully committed to the phlogiston theory. At the same time, there were also comparatively few chemists who were fully committed to Lavoisier's theory either. In that respect, at least, it is difficult to characterize the immediate aftermath of the chemical revolution as "normal science." Earlier supporters of Lavoisier's ideas were, by the 1800s, casting doubts on some of their key assertions. Other chemists, such as the Englishman John Dalton or the Swede Jöns Jacob Berzelius, were coming up with new theoretical frameworks of their own.

The Cornish chemist Humphry Davy had learned the basics of chemistry from William Nicholson's presentation of Lavoisier's ideas to an English audience in his *Dictionary of Chemistry*. By the 1800s, however, following his appointment as professor of chemistry at London's Royal Institution, Davy was starting to cast serious doubt on the adequacy of some of Lavoisier's fundamental ideas. In the first place, Davy's experiments undermined the idea that acidity was due to the presence of oxygen. Davy showed that some acids such as muriatic acid (now called hydrochloric acid) did not contain oxygen. Similarly, he demonstrated that oxymuriatic acid not only contained no oxygen but was, in fact, an element in its own right, which he dubbed chlorine. By 1813 he had succeeded in isolating another similar element, called iodine. Davy made his name primarily by way of spectacular electrical experiments. He used the Royal Institution's powerful and expensive electric batteries to isolate not only chlorine and iodine but sodium and potassium too (Golinski 1992, 2016). The electric battery was a new instrument invented by the Italian Alessandro Volta in the course of his disputes with Luigi Galvani concerning animal electricity. Volta and his French followers argued that the battery produced electricity through the contact of different metals. Davy disagreed, suggesting that the battery's electricity was chemical in origin. Davy also argued against the existence of caloric, which played a key role in Lavoisier's chemical system. Heat, according to Davy, was not an immaterial fluid. Instead, he argued that it was a form of motion. If Davy was to be believed, not only was Lavoisier's oxygen misnamed—it was not an acid former—but neither it nor caloric played the critical part in chemical reactions that Lavoisier had assigned to them.

Lavoisier's definition of an element was largely pragmatic. Chemical elements were just those substances that chemists had been unable to break down into simpler constituent parts. In the hands of the English chemist John Dalton, however, the concept of an element developed different connotations. The idea that matter might be composed of indivisible particles or atoms went back to the Greeks. Seventeenth-century chemists such as Robert Boyle embraced atoms as key features of the new mechanical philosophy. Where Lavoisier considered discussions of the ultimate nature of the elements as being metaphysical and beyond the reach of chemistry, Dalton set out to give the elements a real, physical existence. Dalton was born in northwest England to a Quaker family. At fifteen years old he started a school in Kendall in the Lake District with his brother before later moving to Manchester. During his time in the Lake District, Dalton, who had taught himself the rudiments of Newtonian natural philosophy, developed an interest in meteorology (the study of weather) and kept detailed diaries of local conditions that he published in 1793 as *Meteorological Essays*. The *Essays* helped make Dalton's philosophical reputation, and he employed the same approach toward looking for regularities in large quantities of data to produce his atomic theory of chemical elements (Patterson 1970).

The key difference between Dalton's atomic theory and the corpuscularianism espoused by previous chemical practitioners such as Boyle lay in the fact that Dalton assumed that each element had a unique atom associated with it. Boyle and other eighteenth-century proponents of atomism assumed that all atoms were the same (Thackray 1970). Building on this assumption, Dalton set out to try to define the relative weights of the atoms of the different elements. To do this he had to make a number of assumptions about the ways in which atoms combined together to make different substances. Simply speaking, he argued that elements would always combine together in the simplest possible ways. Since, for example, there was only one known combination of hydrogen and oxygen, Dalton argued that it must be a simple binary compound, with one atom of hydrogen combining with one of oxygen. Where more than one combination was known, more complex combinations (like two to one) were permissible. In the first part of his *New System of Chemical Philosophy* (1808), Dalton used these assumptions to calculate the relative atomic weights of Lavoisier's different elements from the known data concerning the relative quantities of different elements in chemical combinations. Since the relative weight of oxygen to hydrogen in water, for example, was known to be approximately seven to one, Dalton argued that a single atom of oxygen weighed seven times as much as one of hydrogen, the lightest element known (fig. 3.5).

On the basis of his own spectacular electrical experiments, Humphry Davy had concluded that the forces joining chemical elements together into compounds—the forces of chemical affinity as they were known—were electrical in nature. The Swedish chemist Berzelius built on Davy's conclusion along with what he knew of Dalton's atomic theory to come up with an electrochemical view of the way elements combined together. Berzelius classified elements into two kinds—electropositive and electronegative—depending on whether they were released from the positive or negative pole of a galvanic battery when decomposed. The terminology was later reversed to match the conventions introduced by Humphry Davy. The position of any particular element on the scale, with oxygen being the most electronegative and potassium the most electropositive, decided the way that element would combine with others. In atomic terms what this meant was that the individual atoms of the various elements had positive or negative electrical charges associated with them that determined the ways in which they could attach themselves to atoms of other elements to form chemical compounds. Berzelius's comprehensive account of his electrochemical atomic theory was published in 1818 as *Essai sur la théorie des proportions chimiques et sur l'influence chimique de l'électricité*.

Berzelius had originally studied medicine at the University of Uppsala and as professor of chemistry at Stockholm was responsible for teaching pharmacy to medical students. As a result, he was particularly aware that by the early nineteenth century most pharmaceutical texts were increasingly anachronistic by the standards of new chemical theories. It was in the

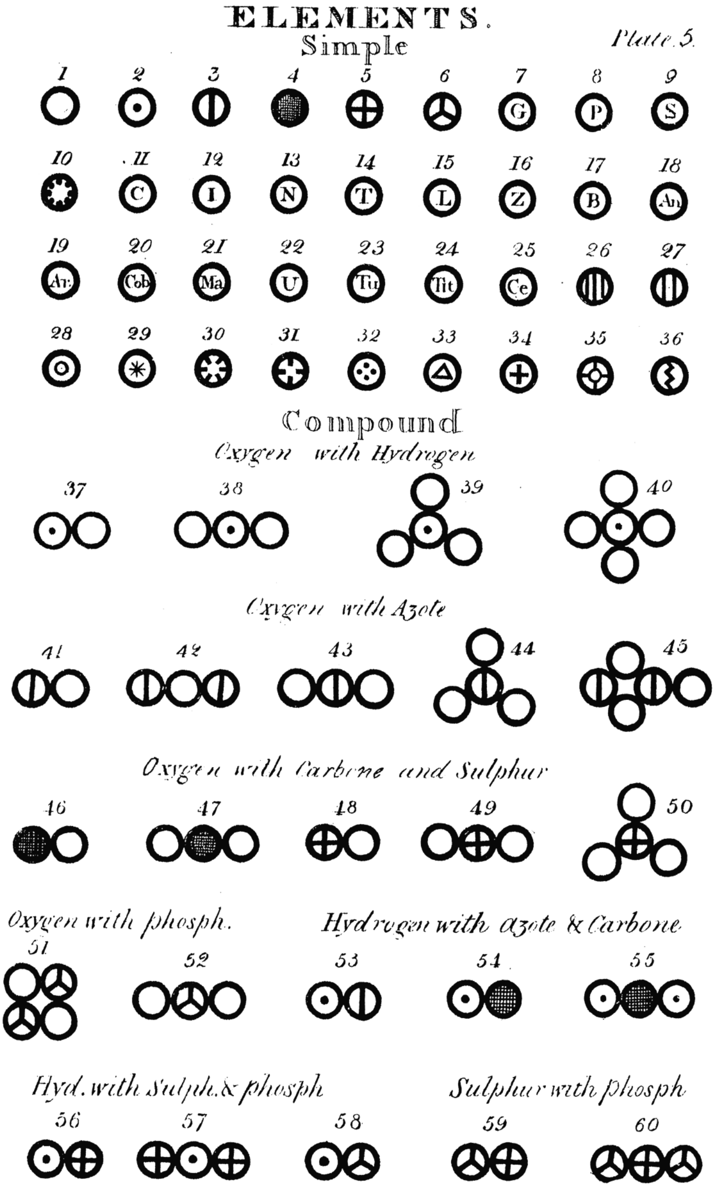

Fig. 3.5. An example of John Dalton's new chemical notation, from his *New System of Chemical Philosophy*. The notation was intended to emphasize the reality of chemical atoms.

context of his efforts to bring pharmacy up to date that he introduced a new conventional nomenclature into chemistry, based on his own electrochemical theories. The various elements were represented by a number of letters and abbreviations (like O for oxygen or Fe for iron) and their combinations represented by sequences of these symbols, with the most electropositive element being written first. Numbers of atoms were represented by numerical superscripts (later subscripts). So carbon dioxide, for example, would be represented as CO^2. Berzelius's new convention was just one of many introduced during the early decades of the nineteenth century and itself underwent many modifications. John Dalton in particular never accepted it, being concerned that the use of conventional symbols to represent the various elements tended to undermine acceptance that chemical atoms had a real physical existence. Dalton used his own notation, which he argued emphasized atoms' physical reality.

Dalton's objection to Berzelius's notation underlines one of the key issues surrounding the atomic theory. Were chemical atoms to be accepted as having a physical reality or were they just a convenient way of talking about chemical reactions and the proportions in which elements combined (Thackray 1972; Rocke 1984)? Dalton himself was convinced that chemical atoms were real. In this he was probably in the minority. Certainly by the middle of the nineteenth century, few chemists took the physical reality of atoms seriously. Chemists regarded the atomic theory—along with other generalizations such as the French chemist Joseph Louis Gay-Lussac's observations that volumes of gases combined with each other in simple ratios—as no more than useful empirical tools. It is not clear that even Berzelius took the reality of atoms too seriously; Dalton clearly thought that he did not. Not even the Russian chemist Dmitri Mendeleev's classification of the chemical elements into the periodic table by atomic weight in 1869 really signaled any decisive and final acceptance of the physical reality of atoms (Gordin 2018). What is clear, however, is that very few if any early nineteenth-century chemists took Lavoisier's revolution of chemistry as definitively establishing a new chemical worldview. On the contrary, it is arguable that little beyond his rejection of the phlogiston theory survived in its original form beyond the new century's opening decades. With the consolidation of thermodynamics and its rejection of heat as an immaterial principle by midcentury, even caloric's pivotal role in chemical reactions was rejected. It seems that early nineteenth-century chemists did not regard their practice as having been reformed decisively. They were still in the process of reforming it.

Conclusions

So what are we to make of the delayed eighteenth-century chemical revolution? It seems that just as we have rejected the traditional account of the Scientific Revolution of the sixteenth and seventeenth centuries we have little choice but to reject the chemical revolution as well—and for many of the same reasons. As we have seen, it is difficult to sustain the notion that chemistry during the sixteenth and seventeenth centuries was somehow left out of the Scientific Revolution. The ideas and practices of a Becher, Boyle, or Paracelsus may seem peculiar to us now, but there is no evidence that they were considered peculiar at the time. Far from it, these practitioners were widely recognized by their contemporaries as important contributors to the New Science. Neither did eighteenth-century natural philosophers regard chemists as being behind the times. Chemists such as Joseph Priestley or Joseph Black were viewed as having made important contributions to natural philosophy as well as chemistry. More generally, contemporaries thought of chemistry as a vital and progressive component of Enlightenment science. Far from being outside the Newtonian synthesis as eighteenth-century practitioners saw it, many chemists were regarded as being in the vanguard (Knight 1978, 1992). Historians increasingly recognize that chemists before Lavoisier made decisive contributions and that their chemistry needs to be understood in the context of their own particular concerns in order to be fully appreciated.

There can be little question, either, that Lavoisier's reforms of chemistry had a major impact. His rejection of the phlogiston theory was in the end decisive and his introduction of quantitative methods and careful measurement set new standards of accuracy in chemical analysis. Again, however, it is also clear that Lavoisier's chemistry cannot be considered as having decisively ushered in the era of modern chemistry. In that sense, at least, his contribution was not revolutionary. As we have seen, very few elements of Lavoisier's chemical system survived the opening decades of the nineteenth century unscathed. Chemists such as Berzelius or Dalton did not regard themselves as working within the confines of a system already established. They were trying to establish their own systems of chemistry. There seems to be something peculiarly arbitrary about the choice of the late eighteenth century and Lavoisier's work as the locus for a unique chemical revolution. More generally, Lavoisier's "chemical revolution" ought maybe to alert us to the problematics of approaching the history of science in terms of a revolutionary perspective at all. On closer inspection, very few revolutions in science turn out to be as coherent or decisive as they might at first have appeared. In that respect, at least, there was nothing peculiar about the revolution in chemistry.

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