

## 6 Theory and Practice

### *The Tools of Revolution*

Revolutions in general succeed either by force of arms or by peaceful persuasion, the force of argument and evidence. The French Revolution began with a mixture of physical force, the power of the people under arms, and argument, the rhetorical force exerted by advocates of the revolution. Force of arms should have no place in science, although coercion can impose new views on the practitioners of science, even in the face of clearly contrary evidence. In Russia under Stalin, the geneticist Lysenko (1898–1976) achieved enormous power and, with Stalin's support, was able to impose on Soviet scientists a theory of inheritance that had already been thoroughly discredited. Authority and patronage belong to the support structure of science, and they can exert less obviously coercive forces on scientists in any society, including our own, determining what research gets funded and published and what gets suppressed. They can determine and maintain what counts as good science. Natural philosophers in England who opposed Isaac Newton when he was president of the Royal Society of London were unlikely to gain academic or government appointments in science.

If Lavoisier and his supporters were going to achieve the revolution in chemistry that they began to regard as necessary, then unlike Stalin they would have to rely on force of argument and evidence. They needed to persuade chemists that the old phlogiston theory was wrong and that the new theory, including its oxygen-based accounts of combustion and acidity, was right. To do this, they needed to perform new experiments and reinterpret old ones. In carrying out their revolution, they devised new innovative apparatus and constructed a chemical language appropriate for the new ideas.

#### Language, the First Tool of Revolution

Language is a tool for communicating ideas and persuading others to accept them. It is also a tool for organizing knowledge and constructing rational arguments to reach conclusions. The chemical revolution was successful partly

because its supporters managed to create a new language for chemistry and to make that language the normal language of chemical debate.

We have already seen that *dephlogisticated air* became *oxygen* and that part of the explanatory role of phlogiston was embodied in the new concept of the matter of heat, *caloric*. We have also seen that Lavoisier relied heavily on the principle of the conservation of matter, generally handled in terms of the conservation of weight, to show that reactants and products had all been identified and accurately measured. Another essential part of Lavoisier's practice was the recognition that chemical reactions were exchanges or regroupings of chemical components and that the nature of a substance was determined by its composition. All these aspects of the revolution required a radical reconstruction of the language of chemistry. And so the first tool of the chemical revolution was a new chemical nomenclature, a new language of chemistry.

Lavoisier himself clearly recognized the importance of language, of chemical nomenclature and of the rules governing that nomenclature. In the preface to his *Elements of Chemistry* (1789), he began by talking about the language of chemistry:

When I began the following Work, my only object was to extend and explain more fully the Memoir which I read at the public meeting of the Academy of Sciences in the month of April 1787, on the necessity of reforming and completing the Nomenclature of Chemistry. . . . [But] while I thought myself employed only in forming a Nomenclature, and while I proposed to myself nothing more than to improve the chemical language, my work transformed itself by degrees, without my being able to prevent it, into a treatise upon the Elements of Chemistry.\*

This statement is not quite accurate. Lavoisier knew very well what he was about. But why did he make the statement? What was the "Memoir" of 1787? What was the new nomenclature? And on what was it modeled? The new nomenclature did not simply spring into existence at Lavoisier's command. Although he took a major role in shaping it, the nomenclature was a product of the Enlightenment passion for thinking clearly, organizing knowledge, and classifying things. There were two main lines of thinking about the language of science that came together in the new chemical nomenclature. One can be traced directly to the work of the great Swedish naturalist Carolus Linnaeus; the other stems from French Enlightenment thinking about the language of science as it took shape in the work of Etienne Bonnot de Condillac.

\*Lavoisier, *Elements of Chemistry*, trans. R. Kerr (Edinburgh, 1789 [1790]), xiii–xiv.

Linnaeus was the inventor of a new classification for plants. This botanical classification was embodied in a nomenclature of which several aspects were to prove important for the subsequent development of chemical nomenclature. First, his nomenclature was based upon the *observable characteristics* of plants (specifically, on the number of sexual parts of the flowers). Second, it was *binomial*: the name of each species had two parts, one identifying the species and the other identifying the genus to which the species belonged.\* Third, it was in an *international* language, an important consideration for a discipline that transcended national borders, and doubly important for Linnaeus, working in Sweden; not many people outside Sweden read Swedish, then or now. Linnaeus chose Latin, traditionally the language of international scholarship. His system enabled him to arrange plants in groups according to their observable characteristics and to communicate unambiguously with naturalists in other countries. That represented a major advance over earlier plant classifications. Linnaeus developed his scheme from the 1730s through the 1750s.

Eighteenth-century reformers of chemistry, and several historians of chemistry since then, have represented the language of chemistry in Linnaeus's day as being full of ambiguities. Salts could be named according to their composition or according to the site where the mineral containing them was found; and of course there could be more than one such site, and so more than one such name. They could also be named after their discoverer, as in Glauber's salt, according to their taste, as in sugar of lead, and in many other ways. Even though eighteenth-century chemical nomenclature was not as chaotic as this suggests, there were enough problems to make the idea of reform seem reasonable. Linnaeus urged his compatriot Torbern Bergman, a professor of chemistry at Uppsala, to try to apply his methods to the classification of chemical substances, which could be viewed as species. Bergman in turn wrote about the project to the French chemist Guyton, and it was Guyton who brought the project to Lavoisier, and thus to the Royal Academy of Sciences in Paris.

The Academy was an institution with rules and bureaucracy. When faced with a problem, its members often resorted to the bureaucratic solution of forming a committee. A committee was appointed to look into the language of chemistry, with Guyton as one of its members and with Lavoisier as secretary. The secretary of a committee prepares the minutes, providing a written record of the committee's deliberations and recommendations. (Perhaps we should include committees as another of the tools of revolution.) In 1787,

\*A genus is a group containing different species that all possess common structural characteristics distinct from those of any other group.

Lavoisier and his committee published their report, *Essay on Chemical Nomenclature*. Phlogiston was out, oxygen and caloric were in, and salts were named according to their composition, considered in two parts, metal and acid. Here was an analog to Linnaeus's binomial classification of plants. As a refinement, the ending of the acid part of a salt's name indicated how much oxygen it contained, as in calcium nitrite and calcium nitrate, where the -ate ending indicated a larger oxygen content than -ite. Some familiar names were retained, for example those of the common metals, but there were new names, corresponding to recently discovered or recently understood substances. Calling the breathable component of the atmosphere *oxygen* rather than *dephlogisticated air* meant that the new theory was embodied in the new language, and the old theory was excluded.

What of Condillac, the other influence on Lavoisier's idea of chemical nomenclature? Condillac had written that language was an instrument of reasoning, an instrument for rational analysis, and an aid to discovery. He had presented mathematics, the language of Newton's physics and astronomy, as the perfect language for science, and then had somewhat eccentrically identified that language with algebra. Mathematics in general, and algebra in particular, had clear rules governing the relations between its terms. The quantities in an algebraic equation could be moved around but not destroyed. Lavoisier's terms—copper and sulphate, mercury and oxygen—could similarly move from one combination to another, but they were not destroyed or diminished in the process. The idea of a chemical equation (although not in its modern form) is implicit in what Condillac says about algebra. Chemistry, if it could only find its right language, would become a science as rigorous in its deductions as mathematical physics.

There was one large question raised by the report on chemical nomenclature that Lavoisier and his colleagues submitted to the Academy. How could one identify the building blocks, the units to be manipulated in accounts of chemical reactions? Lavoisier's answer was *analysis*, a term familiar to chemists and to philosophers. At a stroke, he replaced all the old theories of the elements, and much although not all of the old chemistry of principles, with a chemistry of analysis leading to a provisional list of simple substances. It was a list based upon laboratory experience. That list, unlike philosophically based ones, was always open to change, since what cannot be decomposed and analyzed today may be analyzed tomorrow. Substances that had so far resisted analysis into simpler ones were the building blocks. Sulfur, iron, gold, and oxygen could not be decomposed or analyzed and so they, the simple substances of the laboratory, were building blocks for more complex substances. Copper

sulphate, with its copper and sulfuric acid (itself a compound of oxygen and sulfur), and mercuric oxide, with its mercury and oxygen, were known experimentally to be compounds, and their names indicated their composition.

There were some problem areas. Chemists have always been guided by analogies between substances. That had led Lavoisier to argue that all acids were like those that he had successfully analyzed and thus had to contain oxygen, the acidifying substance or principle. The acids of carbon, sulfur, nitrogen, and phosphorus all fitted this picture. But what about the acid derived from common salt? By analogy, Lavoisier argued that it had to contain oxygen, and so he represented the substance that we call chlorine as a compound of oxygen and a radical that he named but could not isolate. Because chlorine contains no oxygen, we know that he was doomed to failure in his attempts to isolate its unknown radical; but he was not foolish to try. Overall, the new chemical language was what Lavoisier wanted, an instrument of discovery and a tool for persuading others of the truth of his new system of chemistry.

### Balance and Gasometer

The instrument that Lavoisier used with the greatest success to demonstrate the truth of his system was the balance, an instrument with a beam pivoting on a central knife-edge, with a scale pan at each end. Chemical substances are neither created nor destroyed during reactions, and this truth can be shown to hold for any substance that has weight. We shall see later that Lavoisier needed a different instrument to try to show that caloric, the matter of heat, behaved as a simple substance in chemical reactions. This was a problem precisely because caloric had no weight.

The chemical species that Lavoisier recognized were simple or, if compound, were characterized by *constant composition*. The proportions by weight of one constituent to another were always constant in any pure compound. Thus, the proportion of oxygen to carbon in different samples of carbon dioxide was always the same. Constant composition could be demonstrated and confirmed by analysis, with the use of a balance. To use a balance in chemistry was nothing new. Many metallurgists, alchemists, chymists, chemists, mineralogists, and pharmacists had used the balance—some of them for the kind of precise diagnosis that Lavoisier wanted to find out the composition of substances; some of them used it to characterize substances. What was new was Lavoisier's use of the balance as a regulatory instrument. The essential point was to show that the weight of reactants was the same as the weight of products in any chemical reaction. In that case, he could be confident that he had not missed anything. If the weights before and after reaction were different,

that would alert him to the need for further investigation. If there was a weight loss, then something had been lost in the reaction. An unexplained gain in weight showed that some other substance had entered into the reaction and needed to be identified. Lavoisier did not write modern chemical equations, but his idea of chemical reactions corresponded to the form of an equation. The two sides had to balance, and, in the chemical case, that balance involved simple substances and weights.

The balance was the most important instrument in Lavoisier's laboratory. He used two very different classes of balance, everyday ones that gave results good enough to show that he was on the right track and that enabled him to trace the overall nature of a reaction. But he also owned precision balances, made especially for him. He observed that, as "the usefulness and accuracy of chemistry depends entirely upon the determination of the weights of the ingredients and products both before and after experiments, too much precision cannot be employed in this part of the subject; and, for this purpose, we must be provided with good instruments."\* Lavoisier put his money where his mouth was. He spent large sums on the construction of astonishingly precise balances. The best of them, according to one modern estimate, was capable of weighing to one part in 400,000. A comparable instrument had been made for Cavendish in England. Mechanical balances have never been more accurate than these masterpieces of the eighteenth-century's instrument makers' craft.

The balance might be astonishingly sensitive, but it was impossible to guarantee that the substances weighed had a corresponding degree of purity, and the different stages in the manipulation of reagents introduced their own minor errors. The result was that Lavoisier's precision balances were vastly more accurate than his experiments needed. Half a century later, Michael Faraday, one of the greatest experimental chemists ever, stipulated an accuracy of one part in 60,000, a high level of accuracy but much below that of Lavoisier's best instruments. Why then did Lavoisier and his instrument makers strive for and achieve such high precision? The answer lies in a variety of factors, powerful in combination. These include the pride of instrument makers in showing the best of what they could accomplish, the widely shared eighteenth-century passion for precision in science and measurement, and perhaps Lavoisier's own aims for chemistry as a science to rival the other physical sciences. Together, these factors turned Lavoisier's new chemistry into big science, with expensive and dramatic apparatus.

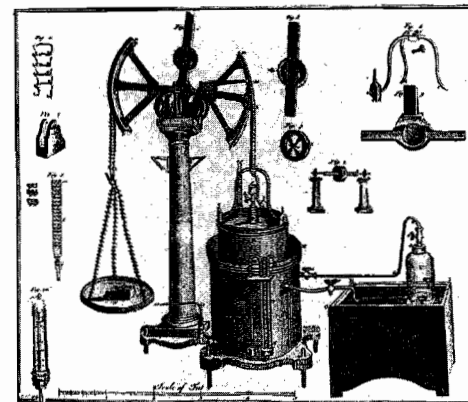
Lavoisier's gasometer was unquestionably the biggest, most expensive, and

\*A.-L. Lavoisier, *Traité élémentaire de chimie*, 3rd ed., 2 vols. (Paris, 1801), 1: 333.

most impressive piece of chemical apparatus in his arsenal. It was the most expensive instrument in all of chemistry up to and beyond the end of the eighteenth century. The gasometer, which controlled and measured the uniform flow and volumes of the gases it dispensed, was an instrument made possible in theory and made necessary in practice by the emergence of gas chemistry as central to the chemical revolution. But, just as Lavoisier's precision balance was more precise than he really needed, so his gasometer was more elaborate and more expensive than laboratory practice required.

The chemistry of gases was central to Lavoisier's chemical revolution. One key experiment was the demonstration of the composition of water. We saw in Chapter 5 that Lavoisier carried out a continuous combustion of hydrogen and oxygen, confirming that water was the sole product of that combustion. To carry out the reaction continuously, he needed to measure and control the rate at which hydrogen and oxygen were supplied to the combustion apparatus. It was easier to do this by volume than by weight. Two volumes of hydrogen combine with one volume of oxygen to form water. Knowing the conditions of temperature and pressure under which the gases were held then made it possible to calculate the weights of the two gases that reacted to form water. In arriving at his results, Lavoisier began with apparatus similar to that used by Hales and Priestley before him. Then, during the 1780s, he went beyond them. Working with colleagues and instrument makers, he invented a true gasometer. The gasometers he used in his research were inexpensive and simple in design and, like his everyday balances, gave good approximate results. When it came to public demonstrations, however, he wanted apparatus that provided precise measurements. When one sees his precision gasometer, it is tempting to conclude that he also wanted apparatus that *looked* impressive and so promised a high degree of precision. Apparatus as well as language can have rhetorical effect.

Lavoisier's precision gasometer looked like the fruit of a marriage between Industrial Revolution engineering and physics, with nearly frictionless roller bearings, manometer gauges, dials and scales, as well as elaborately contrived chains. Each component had to be handcrafted by skilled workers. The resulting apparatus was enormously expensive, the Rolls Royce of chemical instruments, costing the equivalent of more than a quarter of a million dollars in today's money. *Two* such instruments were needed for the demonstration of the composition of water, one for hydrogen and the other for oxygen. Expensive or not, Lavoisier regarded his gasometer as precious and indispensable. Some experiments, he argued, simply could not be done without it. In Lavoisier's hands, chemistry had become big science—quantitative, precise, expen-



### Lavoisier's Gasometer

The key instrument that Lavoisier used for public demonstrations of the composition of water was the gasometer. He claimed it was indispensable for all kinds of work in pneumatic chemistry. It was and is a very impressive piece of equipment. It stands nearly two meters high. Much of the gasometer is made of gleaming polished brass. The gauges are clearly the work of an instrument maker skilled in the production of precision apparatus. The Vaucanson's chain, which rides over the arm of the balance and supports the balance pan, is an exquisite piece of workmanship, and the arms sitting on the frictionless bearings atop the tallest column look remarkably like the heart of an ingenious pumping engine, a product of what was then a still-accelerating industrial revolution.

To use such an instrument or, as Lavoisier needed to do in demonstrating the composition of water, to use *two* such instruments was to exhibit control, authority, and virtual ownership of the field in which the instruments were used. No one else could afford to build gasometers like these. The results that Lavoisier in fact obtained using his gasometers were no better than what others soon obtained with much cheaper instruments; but, as the most expensive pieces of chemical apparatus anyone had ever seen, they showed that chemistry was big science, a science with prestige to rival physics and, perhaps, even astronomy.

■ Antoine-Laurent Lavoisier, *Traité élémentaire de chimie*, 2 vols. (Paris, 1789), plate 8.

sive, and demanding. Lavoisier observed: "It is an inevitable effect of the state of perfection to which chemistry is beginning to approach. This requires expensive and complicated apparatus: no doubt one should try to simplify them, but not at the expense of their convenience, and especially of their exactness."\*

\*Lavoisier, *Traité*, I: 359–60.

For other chemists, Lavoisier's gasometers were, alas, simply too complicated and too expensive to build, so they sought cheaper and simpler alternatives. All converts to Lavoisier's chemistry did however accept, in the years of the consolidation of the chemical revolution, that gasometers were essential instruments of the new chemistry.

### Ice and Fire: Ice Calorimeter and Blowpipe

Conservation of matter was a ruling principle for Lavoisier, and its demonstration was a regulative principle for him. He wanted to show, in every experiment, that nothing had been lost and that the quantities of different simple substances before reaction were the same as those after reaction, no matter what combinations or decompositions (separation into chemically distinct constituent parts) had occurred. For solids and liquids, weighing with a balance enabled him to demonstrate conservation. For gases, he had a choice between weighing directly and measuring volumetrically; from the volume and density of a gas he could then calculate its weight. There were, however, two sets of phenomena that he could not measure by weight or volume: the phenomena of heat and light.

We have seen that the phlogiston theory offered a qualitative explanation for heat in chemical reactions and that Lavoisier, in rejecting the phlogiston theory, had to provide an alternative explanation. Given his goal of making chemistry a demonstrative science, with a logic as rigorous as that of mathematics, he needed to be able to provide an explanation that could be demonstrated quantitatively as well as qualitatively. His solution was to say that there were two simple substances, light and caloric, which could both enter into chemical combination and be released from it. Neither light nor caloric, the old matter of heat and fire, had weight; that is, they were *imponderable* substances. The notion of imponderable substances was well established during the eighteenth century. Electricity was generally understood to consist of one or two imponderable fluids. Magnetism could be similarly explained. So could light and heat. Lavoisier extended the explanatory model by making two imponderable fluids, light and caloric, simple substances for the chemist. Light and caloric, however, were tricky. They could no more be captured and measured by volume than they could by weight. They were very much "wild spirits" that could not be coerced by the chemist in his laboratory. They possessed, in short, some of the same attributes that gases had possessed for chemists before the invention of pneumatic apparatus by Hales, Priestley, and others. That made it difficult for many chemists to accept them as chemical substances. If Lavoisier was to bring these supposed substances into his chemical system, and

convince others that he was right to do so, he had to find a way to quantify them. He had to show that they were conserved through a series of chemical reactions, whether they entered into new combinations or escaped from old ones. If he could not do this, then his theory would fail to explain something that the phlogiston theory claimed that it could explain, and his revolution would be incomplete.

Lavoisier never did manage to measure light. But he was able to measure heat and to build it comprehensively into his theories of chemical change and physical state. Here, as elsewhere, he was making original contributions and also building on the work done by others. The study of heat had been a major preoccupation for eighteenth-century natural philosophers. Scottish researchers had led the way. Joseph Black, whose quantitative work on fixed air provided a fruitful model for later researchers, explored the phenomena of heat as well as those of ponderable substances. He observed that when ice melted, it absorbed heat without changing temperature. A mixture of water and ice would remain at the freezing point and absorb heat until all the ice had melted. Black concluded that since the heat had been absorbed without a rise in temperature, it must have combined with the particles of ice to form water. The heat was present, but it was not apparent as warmth, and so Black called it *latent* heat.\* Following Black, natural philosophers had an explanation for the heat required to change a solid into a liquid, or a liquid into gas, without raising the temperature. Black measured the latent heat of the melting of ice, found that it was constant for a given weight of ice at the freezing point, and so by 1761 gave quantitative form to his theory of latent heat. In describing the latent heat as *combined* with the particles of ice, Black made it possible to claim the process as a chemical one. By measuring latent heat, he was pursuing the same quantitative approach that he had brought to his study of fixed air. Lavoisier had a ready-made home for his interpretation of the phenomena of heat as caused by combination with or release of the chemical matter of heat that he called caloric.

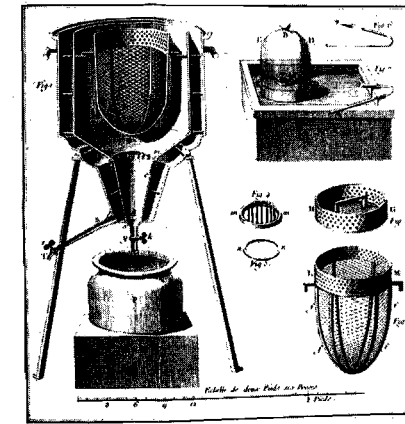
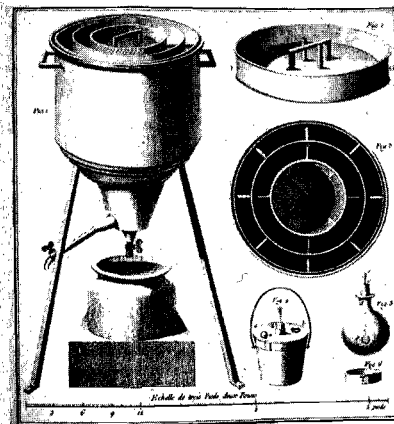
Heat had been a part of natural philosophy, the territory of physics; now it was being claimed as part of the territory of chemistry. That heat was related to change of physical state, from solid to liquid and from liquid to gas, was well known; substances melted or evaporated on heating. Lavoisier explained such transformations in terms of the acquisition of caloric. But what of the relation of substances which existed in chemical combination as part of a solid

\*Black also found that it took different but specific amounts of heat to raise the temperature of the same weight of different substances by the same number of degrees; he thereby laid the foundations for the theory of specific heat.

substance and could be liberated from that combination as gases? Black's fixed air, Lavoisier's carbonic acid gas, was such a substance. So too was oxygen, part of solid metallic oxides but also capable of existing as a gas. Lavoisier interpreted the difference between fixed and free gases in terms of chemical combination with caloric. In mercuric oxide, for example, the substance oxygen was combined with mercury, whereas in gaseous oxygen, the substance oxygen was combined with the substance caloric. Gases were combinations of ponderable substances with imponderable caloric. Given this blending of physics and chemistry, it was fitting that when Lavoisier decided to measure the heat produced in chemical reactions, he did so by collaborating with the younger physicist Laplace.

The instrument that Lavoisier and Laplace invented to measure heats of reaction became known as the *ice calorimeter*, and its design rested squarely on Black's theory of latent heat. It seemed crude compared with Lavoisier's great gasometer, but its design was conceptually elegant. It consisted of a large bucket with a lid which was placed inside two other nesting buckets, both of which could be filled from the top and had faucets at the bottom. At the beginning of the experiment, the two outer nesting buckets were filled with ice, and any water in the inner of these two vessels was run off through the faucet, which was then closed. The ice in the outer vessel would melt gradually, but as long as some ice remained, its temperature would not change from the freezing point. That meant that the inner, or middle, vessel received no heat from the outer layer, since both began at the freezing point; in other words, the middle vessel was thermally insulated from the outside environment in the laboratory. Next, the chemical reaction under investigation was produced in the inside bucket. It might involve mixing two substances, and a modification to the apparatus made it possible to carry out gaseous as well as solid and liquid reactions. The heat released during the reaction would melt ice in the middle vessel, producing water that could be run off and measured at the end of the experiment. Again the principle of latent heat came into play, enabling Lavoisier and Laplace to calculate from the weight of water melted just how much heat had been released during the reaction. Not merely reactions between nonliving substances but also reactions in living animals could be investigated. Respiration, for example, in a guinea pig, was seen as a kind of combustion in the lungs, and it produced heat that would melt ice, and so could be measured.

Alas, thermal phenomena in chemical reactions are more complicated than allowed for in the simple model of combination with caloric or release of caloric. Not until the development of chemical thermodynamics and thermo-



### The Ice Calorimeter of Lavoisier and Laplace

When Lavoisier invited the younger Laplace to collaborate with him in a quantitative study of heat, the invitation was a great compliment to the younger scientist. The results of their joint research were presented to the Royal Academy of Sciences in 1783. The collaboration was symbolic of the union of chemistry with physics and a landmark in the quantification of what Lavoisier regarded as an imponderable substance, that is, a substance without weight. Both scientists were committed to the search for precise measurements, at a time when instrument makers were producing apparatus of unprecedented accuracy.

The measurements that Lavoisier and Laplace obtained with their instrument,

which came to be known as an *ice calorimeter*, were in fact not very accurate; indeed, they were crude when compared with the precision that Lavoisier could obtain with his best balances. They were also crude in comparison with the astronomical data with which Laplace constructed his study *Celestial Mechanics* (1799–1825). But they did amount to a statement about the quantification of the study of heat as an alternative to the phlogiston theory that Lavoisier discredited, and they helped to persuade Laplace to give his significant support to Lavoisier's new system of chemistry.

■ Antoine-Laurent Lavoisier and Pierre Simon Laplace, "Mémoire sur la chaleur," *Mémoires de l'Académie Royale des Sciences* (1780, published 1784), plates 1 and 2.

chemistry in the late nineteenth century (see Chapter 12) did theory truly make sense of the observations. But Lavoisier, aided by Laplace, was striving to expand the reach of quantification in chemistry. Not for the first time, however, theory proved inadequate for interpreting experimental data. But the research program was a clear, rational, and disciplined one, resting on the best of modern science.

Lavoisier's quantitative method was crucial to the creation and to the success of the chemical revolution. Chemistry, however, is a science of qualities as well as of quantities. Chemical analysis has to be qualitative as well as quantitative. Chemists need to know what substances they are dealing with, as well as how much of each of those substances is present. Lavoisier recognized the importance of traditional operations for separating substances that were mixed rather than combined, including solvent extraction, crystallization, and fractional distillation (where substances with different boiling points are distilled at those different temperatures from a mixture).

Lavoisier's operational definition of a simple substance as one that had not yet been decomposed was an invitation to chemists to decompose whatever they could and to identify or discover as many undecomposed substances as possible. Heat was a powerful agent both for separating substances from one another and for decomposing a substance, either on its own or in combination with another substance. Furnaces of all kinds were traditional sources of heat for such purposes, as was the blowpipe, an instrument that Lavoisier took for granted, and so discussed only briefly in his writings. The blowpipe turned out to be one of the most powerful instruments for the identification of new simple substances.

The blowpipe is a narrow tube through which a stream of air can be blown. When applied to a flame, it produces a fine jet at a high temperature. Jewelers, glass workers, and craftsmen working with metal had used the instrument since antiquity, and it had remained a tool of skilled artisans for thousands of years before it was used in chemistry. In the eighteenth century it came into wide use as a specifically chemical instrument, first in Sweden and then, over the next half-century and more, throughout the rest of Europe.

Once it entered chemistry, the blowpipe proved to be a most delicate instrument for the qualitative analysis of mineral ores, revealing the presence of minute quantities of metal in very small samples. Chemists typically worked with samples the size of a mustard seed, and in those samples could detect even half a percent of a particular metal. This was far more sensitive than analysis in solution, the "wet way." The blowpipe led to the discovery of several metals during Lavoisier's lifetime, including nickel, manganese, molybdenum, and tungsten. Because these metals could not be decomposed, Lavoisier duly listed them in his table of simple substances.

### Big Science, and New Borders for Chemistry

Robert Boyle had made chemistry part of the new and eminently respectable natural philosophy based on corpuscular philosophy. His explanations for

chemical phenomena were ultimately compatible with corpuscular science. This made chemistry theoretically a part of what we would call physics. Chemistry as a practical science was something else, and Boyle contributed significantly to chemistry's independence from natural philosophy, at least in the realm of laboratory practice. His classification of chemical substances, based upon experiment, also distinguished chemistry from the rest of natural philosophy. And, as we have seen, Boyle saw no incompatibility between alchemy and his chemistry or chymistry, or between alchemy and atomism. The same is broadly true of Isaac Newton.

The failure of the corpuscular program in chemistry, and the similar failure of Newtonian chemistry, was reinforced by developments in Germany and France. The emergence in Germany of a chemical community whose members claimed independence from medicine and from physical natural philosophy contributed to the autonomy of chemical science. The stress upon experience by the chemists of the French Enlightenment had a similar effect. Chemistry became a science in its own right. Many historians and chemists have claimed that it did so even before the emergence of a recognizable science of physics.

Where do Lavoisier's chemistry and his chemical revolution fit into these developments? His definition of simple substances, based upon laboratory experience, argues for an independent science of chemistry. So does his use of qualitative analogies in classifying substances. Similarly, viewing chemical composition as the key to a classification of minerals and other compounds makes a case for the independence of chemistry. But Lavoisier was also acting and arguing in a way that aimed to give chemistry parity with physical science. He stressed that chemistry should strive for rigor in its arguments, just like mathematics and physics. He did more than any other chemist of the eighteenth century to transform chemistry into a quantitative science, in which sophisticated instruments were used to measure the quantities. His development of expensive and imposing apparatus bolstered the notion that chemistry was comparable with Newtonian physics and astronomy. Like them, it was big science. His collaboration with Laplace in their work on caloric showed that chemistry and physics were capable of being mutually supportive. The important role that he gave to caloric took what some still regarded as a part of physics and made it part of chemistry, as Black's work on latent heat had suggested. In short, Lavoisier helped to transform the theory, the status, and the boundaries of chemical science. The mid-nineteenth century assertion that chemistry was a French science, invented by Lavoisier, did have a grain of truth in its overstatement.

Linnaeus was the inventor of a new classification for plants. This botanical classification was embodied in a nomenclature of which several aspects were to prove important for the subsequent development of chemical nomenclature. First, his nomenclature was based upon the *observable characteristics* of plants (specifically, on the number of sexual parts of the flowers). Second, it was *binomial*: the name of each species had two parts, one identifying the species and the other identifying the genus to which the species belonged.\* Third, it was in an *international* language, an important consideration for a discipline that transcended national borders, and doubly important for Linnaeus, working in Sweden; not many people outside Sweden read Swedish, then or now. Linnaeus chose Latin, traditionally the language of international scholarship. His system enabled him to arrange plants in groups according to their observable characteristics and to communicate unambiguously with naturalists in other countries. That represented a major advance over earlier plant classifications. Linnaeus developed his scheme from the 1730s through the 1750s.

Eighteenth-century reformers of chemistry, and several historians of chemistry since then, have represented the language of chemistry in Linnaeus's day as being full of ambiguities. Salts could be named according to their composition or according to the site where the mineral containing them was found; and of course there could be more than one such site, and so more than one such name. They could also be named after their discoverer, as in Glauber's salt, according to their taste, as in sugar of lead, and in many other ways. Even though eighteenth-century chemical nomenclature was not as chaotic as this suggests, there were enough problems to make the idea of reform seem reasonable. Linnaeus urged his compatriot Torbern Bergman, a professor of chemistry at Uppsala, to try to apply his methods to the classification of chemical substances, which could be viewed as species. Bergman in turn wrote about the project to the French chemist Guyton, and it was Guyton who brought the project to Lavoisier, and thus to the Royal Academy of Sciences in Paris.

The Academy was an institution with rules and bureaucracy. When faced with a problem, its members often resorted to the bureaucratic solution of forming a committee. A committee was appointed to look into the language of chemistry, with Guyton as one of its members and with Lavoisier as secretary. The secretary of a committee prepares the minutes, providing a written record of the committee's deliberations and recommendations. (Perhaps we should include committees as another of the tools of revolution.) In 1787,

\*A genus is a group containing different species that all possess common structural characteristics distinct from those of any other group.

Lavoisier and his committee published their report, *Essay on Chemical Nomenclature*. Phlogiston was out, oxygen and caloric were in, and salts were named according to their composition, considered in two parts, metal and acid. Here was an analog to Linnaeus's binomial classification of plants. As a refinement, the ending of the acid part of a salt's name indicated how much oxygen it contained, as in calcium nitrite and calcium nitrate, where the -ate ending indicated a larger oxygen content than -ite. Some familiar names were retained, for example those of the common metals, but there were new names, corresponding to recently discovered or recently understood substances. Calling the breathable component of the atmosphere *oxygen* rather than *dephlogisticated air* meant that the new theory was embodied in the new language, and the old theory was excluded.

What of Condillac, the other influence on Lavoisier's idea of chemical nomenclature? Condillac had written that language was an instrument of reasoning, an instrument for rational analysis, and an aid to discovery. He had presented mathematics, the language of Newton's physics and astronomy, as the perfect language for science, and then had somewhat eccentrically identified that language with algebra. Mathematics in general, and algebra in particular, had clear rules governing the relations between its terms. The quantities in an algebraic equation could be moved around but not destroyed. Lavoisier's terms—copper and sulphate, mercury and oxygen—could similarly move from one combination to another, but they were not destroyed or diminished in the process. The idea of a chemical equation (although not in its modern form) is implicit in what Condillac says about algebra. Chemistry, if it could only find its right language, would become a science as rigorous in its deductions as mathematical physics.

There was one large question raised by the report on chemical nomenclature that Lavoisier and his colleagues submitted to the Academy. How could one identify the building blocks, the units to be manipulated in accounts of chemical reactions? Lavoisier's answer was *analysis*, a term familiar to chemists and to philosophers. At a stroke, he replaced all the old theories of the elements, and much although not all of the old chemistry of principles, with a chemistry of analysis leading to a provisional list of simple substances. It was a list based upon laboratory experience. That list, unlike philosophically based ones, was always open to change, since what cannot be decomposed and analyzed today may be analyzed tomorrow. Substances that had so far resisted analysis into simpler ones were the building blocks. Sulfur, iron, gold, and oxygen could not be decomposed or analyzed and so they, the simple substances of the laboratory, were building blocks for more complex substances. Copper