

7 Atoms and Elements

Lavoisier's system of chemistry depended on the consistent use of a new experimental method, at least, one that had not previously been systematically applied in chemistry. Lavoisier asserted that he would be guided only by experimental evidence, by the facts of experience. Besides the evidence of the senses, the most convincing chemical evidence for Lavoisier was what could be measured and built into a quantitative system. Quantification opened the way to mathematical deductive reasoning. Lavoisier believed that mathematical reasoning based on measurement could make chemistry as rigorous and prestigious as Newtonian physics. Measurement of any substance that had weight meant the use of the precision balance or the conversion of measurements of volumes into the corresponding weights. We have also seen his work with Laplace on the measurement of heat, using the ice calorimeter to try to bring quantitative rigor to the study of caloric. Conservation of matter was the key.

For Lavoisier, weights were not simply numbers to tally. They were ways of regulating, shaping, and validating chemical experiments and theorizing. Chemical analysis and weighing went hand in hand. Together, they gave Lavoisier a way to replace the old ideas about elements with a new concept of simple substances of the laboratory. Chemical theories based on anything other than experimental evidence were, for Lavoisier, simply worthless, and that went for every theory of the elements that had been proposed by his predecessors.

Talking about true elements as indivisible atoms was metaphysics, not chemistry. Lavoisier insisted on making that point:

If, by the term *elements*, we mean to express those simple and indivisible atoms of which matter is composed, it is extremely probable that we know nothing about them; but, if we apply the term *elements*, or *principles of bodies*, to express our idea of the last point which analysis is capable of reaching, we must admit, as elements, all the substances into which we are capable, by any means, to reduce bodies by decomposition.*

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

As we saw in Chapter 5, that did not mean that substances not yet decomposed were truly elementary. They might very well be compounds, and chemists might, one day in the future, be able to decompose them. Lavoisier stressed the provisional nature of his list of "elements": "Thus, as chemistry advances towards perfection, by dividing and subdividing, it is impossible to say where it is to end; and these things we at present suppose simple may soon be found quite otherwise. All that we dare venture to affirm of any substance is, that it must be considered as simple in the present state of our knowledge, and as far as chemical analysis has hitherto been able to show."* Lavoisier had a well-founded hunch that some substances he had been unable to decompose would prove to be compound, although he could not yet say what their constituent elements were. The alkalis, soda and potash, were substances that he was sure were compounds, but he had to list them as simple because he could not yet decompose them. In their case, Lavoisier's hunch was right. In another instance, that of chlorine, his certainty that it was compound was to prove unfounded. Later chemists showed ingenuity and spent a good deal of effort trying to decompose Lavoisier's "elements." Sometimes, as we will see, they succeeded, discovering new elements. Sometimes they failed.

Note that Lavoisier, like Boyle before him, distinguished between ultimate atoms and the undecomposed substances of the laboratory, what we call chemical atoms and physical atoms. There was no accessible way in Lavoisier's system to connect ultimate atoms with chemical elements. Sticking to the facts in Lavoisier's way meant avoiding making any connection between atoms and elements. There was, philosophically, a profound distinction between them. For the next two generations, chemists were to argue about that distinction. Some were sure it was necessary, some were equally sure that it was unnecessary and simply wrong.

John Dalton, Atoms and Elements: The Birth of a Chemical Atomic Theory

John Dalton (1766–1844) was the most influential of those who argued that chemical atoms were also physical atoms. He was the inventor of a truly chemical atomic theory, where atoms were the least part of chemical elements. He also discovered a series of numerical laws and rules expressing the rules governing chemical combination.

Dalton's father was a weaver and a Quaker, a dissenter rather than a member of the established church in England. As a Quaker, Dalton, like Joseph

*Ibid., 1: 194.

Priestley before him, was unable to attend either of the ancient universities. He was largely self-taught in science, and in 1793 began to teach mathematics and natural science in a dissenting academy in Manchester. He went on to become a major research chemist. By the time he died in 1844, he was internationally renowned and one of Manchester's most famous citizens.

Dalton's interest in science began not with chemistry but with meteorology, the science and study of weather. He was fascinated by the changeable and rainy climate of England's Lake District, where he was born and where he taught before moving to somewhat less rainy Manchester. From making meteorological observations, he began to think about and experiment on vapor pressure, the pressure exerted by gases or vapors. He also gave some attention to the composition of the atmosphere, mainly to nitrogen and oxygen. And he began to look at the solubilities of different gases in water. All these interests led him in 1801 to what we now know as *Dalton's law of partial pressures*, which states that in a mixture of gases, each gas exerts its partial pressure, the same pressure that it would exert if it alone were present. The total pressure exerted by a mixture of gases, like the atmosphere, is the sum of the partial pressures of the different gases present. It is as if the particles of one gas ignore the particles of other gases present in a mixture. Why would they behave like that?

Here, Dalton found inspiration in his reading of Isaac Newton. He found what was for him a crucial passage in Newton's *Opticks*, and he copied it into his own notebooks. "It seems probable to me," wrote Newton, "that God in the Beginning form'd matter in solid, massy, hard, impenetrable, moveable Particles While the Particles continue entire, they may compose Bodies of one and the same Nature and Texture in all Ages."* If the particles changed, if they broke in pieces or were worn down, then the substances that they composed, for example water and earth, would change their nature. What Newton meant by these statements is one thing and has been widely debated. What Dalton came to understand by them was another. He concluded that different simple substances or elements, such as oxygen or nitrogen, consisted of atoms. All atoms of a given chemical substance were identical with all the other atoms of that substance and different from the atoms of any other substance. That meant that Lavoisier's elements had to be considered as consisting of ultimate and indivisible atoms.

In the gaseous state, according to Dalton, atoms of the same kind repelled one another. As he put it, each atom "supports its dignity by keeping all the rest . . . at a respectful distance." That was why gases mingled evenly in the at-

*Isaac Newton, *Opticks* (New York: Dover, 1952), 400.

mosphere, instead of those with heavy atoms sitting at the bottom, near the ground, and the lighter ones occupying a higher place. Chemical analysis and synthesis were merely the separation or reunion of atoms. "No new creation or destruction of matter is within the reach of chemical agency. We might as well attempt to introduce a new planet into the solar system, or to annihilate one already in existence, as to create or destroy a particle of hydrogen."*

At this point, it is easy to imagine what Lavoisier, if he had been able to escape the guillotine, might have had to say to Dalton. Lavoisier's views about atoms and elements were very different from Dalton's. Lavoisier insisted that ultimate atoms were metaphysical and that we have no knowledge of them from experiment. He asserted that ultimate elements were also metaphysical. What he was willing to call chemical elements were the last products of analysis, and as our powers of analysis grew, he argued, the number of elements would change. Chemical elements had nothing to do with atoms, and chemical atoms were nothing but a fiction.

Lavoisier, given his philosophy and the chemical theories that he faced, was right to take the line that he did. But Dalton made a crucial breakthrough. He believed that the ultimate atoms of different chemical elements were distinguished by having different *weights*. All the atoms of a given element had the same weight. These were assumptions. Dalton made one further assumption. Lavoisier and others had shown that different chemical compounds could be characterized by the different combining weights of their constituents. Each compound had a constant composition.† There was, for example, a constant ratio between the weight of mercury and the weight of oxygen which produced mercuric oxide. Similarly, the ratio by weight between sulfur and oxygen in copper sulphate was constant, and it was different from the constant ratio between the same elements in copper sulphite. Dalton suggested that these ratios were the ratios of the relative weights of the atoms. Thus, if we agreed to take the relative weight of one substance as a reference, we could call that the atomic weight of the reference element. Then, by means of quantitative analysis, we could arrive experimentally at the atomic weights of every other element. But we could not do this without making more assumptions.

Dalton proposed, first, that like atoms repelled one another. That meant

*John Dalton, *A New System of Chemical Philosophy* (London: Peter Owen, 1965), 162–63.

†This depends on what counts as chemical combination. If metallic alloys and liquid solutions are combinations, as some chemists around 1800 believed, then obviously not all compounds are characterized by constant composition. Claude-Louis Berthollet was among the leading chemists who adopted the view that solutions and alloys were chemical compounds, and he rejected Dalton's laws of constant combining proportions (for these laws, see below). Dalton took the view that if composition was not constant, then the substance was not a chemical compound.

that elements, which were made up of like atoms, could not exist in diatomic molecules, where a molecule is a chemical combination of atoms. So oxygen and nitrogen particles in the atmosphere had to be single atoms of oxygen and nitrogen. He was wrong; we know that oxygen and nitrogen are diatomic gases, that is, that their molecules have two atoms apiece. But he needed working assumptions to bring order out of chaos. Both his studies of partial pressures and his search for simplicity in nature favored the rule that like atoms repel one another. And simplicity was something that Newton had recommended. Nature, according to Newton, is very simple.

Dalton's second assumption or rule was that when only one combination between two elements can be obtained, we should assume that its molecules consist of one atom of each element, unless, he allowed, "some cause appear to the contrary."* Ammonia would then be made up of one atom of nitrogen and one of hydrogen. But this is wrong, since we know that ammonia contains three atoms of hydrogen and one of nitrogen. If we take hydrogen as our reference standard and give it the atomic weight of one, then Dalton's formula means that the atomic weight of nitrogen is roughly 4.7. It isn't; we know that it is 14, three times as much as Dalton's assumption indicates. Dalton was wrong, but his argument was reasonable and his experiments were sound. They were also carried out, as Priestley's had been, with very simple and readily available apparatus. In spite of Lavoisier's claim that expensive apparatus was now essential, it was clearly possible to obtain important results without spending a fortune on instruments and apparatus.

When there were two combinations between the same elements, Dalton proposed that the simpler one should be assumed to be a 1:1 combination and the more complex a 1:2 combination. Thus, the gaseous combinations of carbon and oxygen would be carbon monoxide (one atom of carbon plus one of oxygen) and carbon dioxide (one atom of carbon plus two of oxygen), which is right.

Dalton's combining rules can be generalized in what is now known as *Dalton's law of multiple proportions*. When two elements combine in a series of compounds, the ratios of the weights of one element that combine with a constant or fixed weight of the second are small whole numbers. That follows from Dalton's account of the combining ratios of atoms. Because the molecular weight of a compound is proportional to the number of atoms of each element that forms part of that compound, and because atoms combine in the ratio of small whole numbers, combining weights will similarly be in the ratio

*Dalton, *A New System*, 167.

of small whole numbers. We can easily see how the law of multiple proportions applies to a series such as that of the oxides of nitrogen, N_2O , NO , and N_2O_4 , or of the combinations of hydrogen and oxygen, H_2O and H_2O_2 , using modern formulas which enable us to predict the combining weights in each case. The oxides of iron, FeO , Fe_2O_3 , and Fe_3O_4 , make up another series that obeys the law of multiple proportions.*

Dalton proposed a series of chemical symbols corresponding to each element or, in different contexts, to one atom of each element, and drew groups of these symbols to represent molecules. This meant that chemical formulas could represent the number of atoms in a compound, not merely the relative combining weights.

Let us take stock for a moment. Dalton was dealing with *combining weights* and with a *chemical atomic theory* that he invented. That led him to propose and determine a system of *atomic weights*. He both assumed and strengthened the *law of constant composition*, that each chemical compound has a fixed composition. He showed that chemical elements (whether provisionally defined, following Lavoisier, or taken as ultimate) combine in predictable proportions by weight, and he suggested rules for interpreting different compounds formed by the same two (or more) elements. This corresponds to the *law of multiple proportions*.

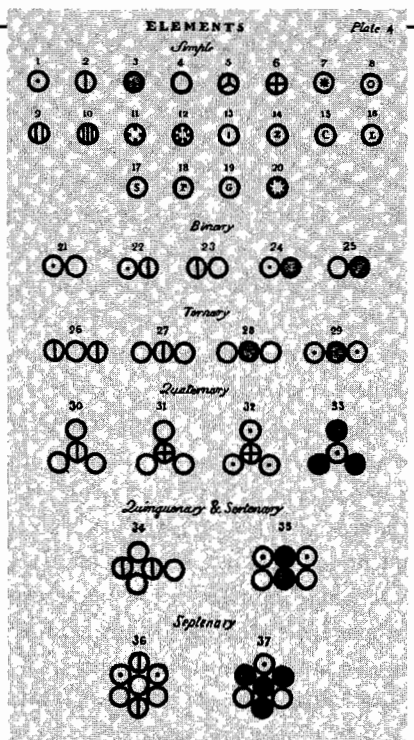
Most chemists could agree about combining weights, constant composition, and multiple proportions. Most chemists were also delighted at the possibility of a system of formulas that would indicate the relative amounts of elements in compounds. Such formulas were a wonderful help with classification, as well as provided a valuable shorthand that made clear the difference between nitrites and nitrates, sulphites and sulphates. Formulas, combining weights, constant composition, and multiple proportions offered the possibility of a research program that would determine combining weights and formulas so as to bring order to chemistry. Dalton's discoveries and rules helped nineteenth-century chemists to find order and predictability in the richness of chemical experiments, in the same way that the search for tables of affinities had served many eighteenth-century chemists. Dalton's contributions were among the most important in the history of chemistry.

*Dalton's simplicity rules here give him incorrect formulas. The simplest combination of hydrogen and oxygen, water, should be HO according to Dalton, whereas the correct formula is H_2O ; hydrogen peroxide would have been HO_2 for Dalton, but it is in fact H_2O_2 . Similarly, the simplest compound of nitrogen and oxygen was NO for Dalton, but it is N_2O for us. Although Dalton's simplicity rules sometimes led him to wrong formulas, they were entirely compatible with his laws of combining proportions.

John Dalton's Atomic Symbols

Dalton's table of chemical elements is the first in which chemical atoms and chemical elements appear in a one-to-one correspondence. Chemical elements for Dalton, as for Lavoisier, were substances that could not be decomposed into simpler substances. But Dalton went beyond Lavoisier, claiming that each chemical element was made up of identical and indivisible atoms, which were the element's smallest parts. Chemical elements were distinguished from one another by their chemical qualities and also by the different weights of their constituent atoms. Dalton did not claim to know the absolute weights of atoms, but made claims about their *relative* weights.

In Dalton's table, the first element is hydrogen, and the relative weight of an atom of hydrogen is 1. The fourth element is oxygen, with relative weight 7. That means that an atom of oxygen is 7 times heavier than an atom of hydrogen. Dalton obtained that result by observing that an atom or the least part of steam or water (no. 21 on the table) contains seven times more oxygen by weight than it does hydrogen; we call the least part of steam or water a molecule. Dalton further assumed that the molecule of water, since it was the simplest compound of oxygen and hydrogen, contained one atom of each element. If he had had more accurate data and



made the same assumption, he would have concluded that an atom of oxygen was 8 times heavier than one of hydrogen. Using today's knowledge that a molecule of water contains two atoms of hydrogen and one of oxygen, and that each molecule has eight times more oxygen than hydrogen by weight, we arrive at our figure of 16 for the atomic weight of oxygen.

■ John Dalton, *A New System of Chemical Philosophy* (London, 1808), plate 4.

What Lavoisier had said about the unknowability of ultimate elements and the distinction between chemical species and physical atoms continued to trouble a lot of chemists long after the publication of Dalton's ideas in the early 1800s. Was it possible to reject Dalton's chemical atomic theory while adopting everything else that he offered? A significant minority of Dalton's con-

temporaries answered with an emphatic yes. Take the combination between hydrogen and oxygen. Everyone could agree that eight parts by weight of oxygen combined with one part by weight of hydrogen. Why not simply say that eight parts by weight of oxygen were *equivalent* to one part by weight of hydrogen, and then present that empirically determined result by saying that if one took the *equivalent weight* of hydrogen as 1, then the equivalent weight of oxygen was 8. Formulas could then represent the number of equivalent weights involved in a compound; carbon dioxide would have one equivalent of carbon to two equivalents of oxygen. For practical purposes, at least in the early nineteenth century, it made no difference whether chemists used a system of atoms or of equivalents. Later on, as we shall see, it did make a difference. But when Dalton was awarded one of the first two Royal Medals from the Royal Society of London, the president of the Society, Humphry Davy, made it clear that the award was for Dalton's laws of combining proportions rather than for his hypotheses about atoms. Davy went on to describe Dalton as the Kepler of chemistry. Johannes Kepler had come before Newton and had made great contributions to astronomy, but in England Newton was regarded as the one who finally made sense of the laws governing the planets. Dalton, by implication, would take second place to the Newton of chemistry.

Humphry Davy and the Voltaic Pile: Laws and Order

Humphry Davy (1778–1829) was a self-made man, a woodcarver's son who later, as the leading British chemist of his day, became president of the Royal Society of London. He made chemistry fashionable in London. Carriages queued up to bring people to his lectures or to read bulletins of his health when he was ill. He was constantly probing the nature and number of chemical elements, and in doing so he made the most dramatic use of an instrument invented by Alessandro Volta. Davy kept returning to questions about the existence and nature of atoms. And he, even more than John Dalton, saw himself as the Newton of chemistry, the one who brought laws and order into the chemical laboratory.

Before 1800, electricity meant static electricity, generated by friction. It could be stored in jar-like condensers, and a number of these condensers could be discharged simultaneously, like an artillery battery, producing a very hefty shock—up to half a million volts. The sparks from such discharges could ignite gas mixtures and decompose relatively small samples of some substances. Then in 1800, Volta published a description of a new piece of apparatus, the *electric pile*. It was called a pile because it consisted literally of a pile of alternating disks of metals and blotting paper moistened with a salt solution. It was

also soon called a battery, by analogy with the battery of condensers used to store static electricity. When the top and bottom of the pile were connected, a continuous current flowed. It was not immediately obvious that this continuous kind of electricity was the same as frictional electricity. But it was clear that chemical action and the electrical action of the pile were connected in some fundamental way. Here was an immediate challenge, one that Davy described as "an alarm bell to the slumbering energies of experimenters in every part of Europe."^{*}

The original form of the pile, a column of disks, soon gave way to a trough containing a salt solution, into which metallic plates were dipped, maintaining the original alternation of metals and salt solution but in a different form. Researchers observed that when the current passed through salt solutions, gases evolved and metals deposited on the wires or plates dipping into the solutions and connected to the opposite ends of the pile. As the source of a continuous electric current, the new form of the instrument was a recognizable ancestor of today's electric batteries. Since it produced chemical decomposition, it was an instrument of chemical analysis, an addition to chemists' arsenal of tools for breaking down compounds. It was also, apparently, an instrument that could be made more and more powerful, given that there was no theoretical limit to the size or number of metallic disks. A bigger and more powerful battery would be a more powerful instrument for chemical analysis.

Davy was the most successful of those who accepted the challenge implicit in Lavoisier's definition of elements as the last products of analysis. If he could decompose one or more of Lavoisier's elements, then he would have discovered new ones. As Lavoisier had observed, there was no telling where this process of discovery through decomposition or analysis would lead. Davy aimed to find out. He produced a series of ever more powerful electric piles. In 1806 he lectured to the Fellows of the Royal Society on the chemical agencies of electricity. He concluded, from a beautifully controlled and reasoned chain of electrochemical researches, that chemical affinity and electrical attraction were different manifestations of the same power of matter. He suggested that substances differed chemically in their response to an electric current, in a way that made it possible to rank them in a series according to their electropositivity or electronegativity. Metals, for example, were electropositive, while oxygen was electronegative. Electropositive substances were those that, in the course of electrolysis, went to the negatively charged pole, while elec-

^{*}Royal Institution of Great Britain, H. Davy MS 1.

tronegative substances went to the positively charged pole, since opposite charges attract one another.

If chemical affinity and electrical attraction were ultimately the same, then chemical attraction was a form of electrical attraction, so that electropositive and electronegative substances would attract and combine with one another. Their combination could be overcome by a more powerful electrical attraction (e.g., from a strong electric battery) and electricity would therefore be able to produce chemical decomposition. Davy applied this thinking to the fixed alkalis, soda and potash. He knew, following the work of French chemists, that ammonia was an alkali and that it was a compound of hydrogen and nitrogen. By analogy, might not the caustic alkalis soda and potash also be compounds? He knew that Lavoisier had suggested that these alkalis were compounds, but Lavoisier, unable to decompose them, had listed them as elements, at least for the time being. Davy used a powerful voltaic battery to show that soda and potash each contained previously unknown metals that reacted violently with oxygen and even with water. They had an extraordinarily high affinity for oxygen. He named these metals sodium and potassium. They were new elements, and Davy was their discoverer. Apart from personal pride, there was national pride involved too, since the Napoleonic Wars were in full swing, and France and England were enemies. Davy's success was even sweeter because it could be seen as a blow struck against French chemistry. Lavoisier had invented the name *oxygen* to identify the gas with acids; oxygen, as we noted before, means "acid producing" or "acid generating," and oxygen for Lavoisier was the acidifying principle. Davy had shown that oxygen was a component of the caustic alkalis, which were the opposite of acidic, and he went on to show that oxygen was also a component of the alkaline earths.

Using the voltaic battery, Davy showed that the alkaline earths, like the caustic alkalis, were compounds containing oxygen and previously unknown metals. His characterization and naming of the alkaline earth metals followed his discovery of them: *barium*, *strontium*, *calcium*, and *magnesium* are the names he invented for these metals.^{*} Like the names *sodium* and *potassium*, they are still in use today.

The voltaic battery provided Davy with a tool for analysis. Because it was a tool that seemingly could be made ever more powerful, Davy hoped that it might reveal the true or ultimate elements of bodies, not just the so-called el-

^{*}In 1808 Davy first called magnesium *magnium*, since *magnesium* had been used for another metal, which we now call manganese; in 1812, Davy withdrew *magnium* and used *magnesium*, in spite of its former use.

ements that Lavoisier was content with. It all depended on what counted as the last products of analysis. If all that was meant was a list based on the current state of chemical analysis, and if that analysis was almost bound to go further in the future, then the products of analysis were not true elements as far as Davy was concerned. If, on the other hand, the last products of analysis were truly the last such products and no deeper analysis was possible, then chemists would have discovered true elements. How could a chemist know when he had reached the end of analysis? Davy was convinced that building voltaic piles of greater and greater size and power would take him to that end. He was also convinced, like a good Newtonian, that nature was very simple. He believed that this might well mean that there were very few ultimate elements, perhaps even just one.

Instead of reaching this goal, Davy's work with the voltaic pile had led him to the discovery of several new elements, which was frustrating. As if that was not bad enough, another approach that he took to a related problem produced a similarly frustrating result, although in a different way. Lavoisier had said that all acids contained oxygen, and from that rule it followed that the acid produced from sea salt (hydrochloric acid) must contain oxygen. Since analogies are important in chemistry, and Lavoisier's argument here was based on assumed analogies among all acids, Davy began by assuming that Lavoisier was right. He tortured the green gas that he obtained from the acid produced from sea salt, trying to pry its oxygen away from it. He burned diamonds in the gas, using a burning glass to produce the necessary high temperature, but he found no oxides of carbon. He passed the gas between the white-hot arcs of a carbon arc lamp and again failed to detect any oxides of carbon. His consistent and total failure to find oxygen in the green gas, and thus to show the presence of any oxygen in the acid produced from sea salt, was another blow to Lavoisier's theory of acidity. So Davy rejected Lavoisier's name for the supposed constituents of that particular acid, which Lavoisier had called oxymuriatic acid. In 1810, Davy came up with his own name for the green gas obtained from the acid, *chlorine*, which indicates greenness, as it does in chlorophyll, but which says nothing about acid making. The name we use for the acid, hydrochloric acid, was in use within two years of publication of Davy's paper on chlorine.

Davy then noticed an analogy between the salts of hydrochloric acid, that is, chlorides, and those of fluoric salts. He inferred the existence of another substance analogous to chlorine, and in 1813 named it *fluorine*.^{*} Because of its extreme reactivity, he was unable to isolate it.

^{*}The name *fluorine* was suggested to Davy by the French chemist and physicist André Marie

In spite of the Napoleonic Wars, Davy was issued a passport for France and French-occupied Europe, and in 1813 he was in Paris, where he met his French rival-colleagues. One of them, André Marie Ampère, behaved more as a colleague than as a rival, and he gave Davy a sample of a dark solid that produced a violet vapor. Davy, who had a traveling laboratory kit in his carriage, rapidly characterized the new substance, recognized that its chemical properties were analogous to those of chlorine, named it *iodine*, and sent a paper on it to the Royal Society of London. Ampère's colleagues in Paris were not pleased that an enemy Englishman had scooped them.

Fluorine (inferred but not isolated by Davy), chlorine, and iodine are three elements in the group that we call halogens. They further extended the list of elements that Davy discovered, and further frustrated his search for underlying simplicity and a very few ultimate elements.

Since Davy did not believe that the elements he kept discovering were ultimate elements, he also did not believe that each element had had its own unique and indivisible atoms. He did not buy Dalton's account of atoms and elements (that was why his award of the Royal Medal to Dalton was such a backhanded compliment). Instead, Davy speculated that there might be just one kind of ultimate atom, a center of forces that might be like Newton's gravitational force. This kind of atomism would make transmutation a theoretical possibility, and Davy did give some thought to transmutation, and even, on occasion, thought that he had come near to achieving it. What were acceptable to Davy were the notions of equivalent rather than atomic weights and Dalton's numerical laws of combining proportions, and he used them in pursuing his very differently motivated researches.

John Dalton's atomic theory and his combining laws were the single most influential package in shaping nineteenth-century chemistry. It was Davy, however, and not Dalton, who gained the greater glory in the Royal Society. But the Royal Society was not the whole world of chemical science. There are very good arguments for identifying Davy's contemporary and rival, the Swedish chemist Berzelius, as the grandfather and perhaps the godfather of nineteenth-century chemistry.

Berzelius: The Uncrowned King of European Chemistry

Jöns Jacob Berzelius (1779–1848) brought together the ideas of Lavoisier with those of Dalton and added his own ideas about electrochemistry. His skill in

Ampère, whose name is commemorated by the use of *ampere* as a measurement for electrical currents, just as Volta's name is commemorated by *volt* as a measure of electrical intensity or potential difference.

the laboratory, his enormously influential textbooks, and the energy with which he promoted his ideas made him the most authoritative chemist in the first half of the nineteenth century. He developed the first chemical notation that is recognizably similar to our own, in which letters are used as chemical symbols and the numbers of atoms of each species in a compound are clearly indicated. He applied his electrochemical and atomic ideas systematically, so that composition, reactions, properties, classification, and affinities could all be explained by the same theory. He was the architect of the most successful chemical theory in his lifetime, and it made a truly unified theory of chemistry possible, to a degree not achieved before.

He was Davy's rival in electrochemistry, using the voltaic pile much as Davy did to explore the decomposition of substances. But his concern was not with finding ultimate elements. What he wanted was an understanding of the chemical nature of the atoms of different substances, and he regarded that nature as derived from the electrochemical character of the atoms. Like Davy, he recognized the importance of electronegativity and electropositivity, most clearly revealed in electrolysis, when an electric current was passed through salt solutions. Oxygen was a special element for Berzelius, as it had been for Lavoisier, but in different ways and for a different reason. Berzelius believed that oxygen was the most electronegative element, so he placed it at one end of a table of substances ranked according to the electrical nature of their atoms and corresponding in its order to a table of chemical affinities. The unique electrical character of each element explained its unique chemical behavior, and Berzelius used this insight to classify salts and minerals. This was a matter of great economic significance in a mining country like Sweden, and it may have contributed to Berzelius's rapidly growing reputation in the German states, where mining was also the leading industry.

Atoms had distinct electrical natures, and so did radicals, which were stable groups of atoms that remained together through successive chemical reactions. Every acid contained its characteristic radical. Acid radicals were all electronegative—they all migrated to the positive pole during electrolysis, while metals, being electropositive, migrated to the negative pole. Every chemical compound, according to Berzelius, had an electropositive and an electronegative part, held together by their electrochemical affinities. Here was the foundation of electrochemical dualism in chemistry, and it matched the binary nomenclature that had originated with Linnaeus and been established in chemistry by Lavoisier and his collaborators. Copper sulphate, for example, has positive copper combined with negative sulphate, and the sulphate "radical," as Berzelius called it, was possible because its two constituents (dualism

again) differed in the degree of their electronegativity. The course of a chemical reaction depended on how far apart reactants and their constituents were on an electrochemical scale of affinities; similar atoms repelled each other, while unlike ones attracted each other.

Berzelius's use of the atomic theory and of a theory of electrochemistry to account for chemical reactions worked best for salts. The chemistry of salts had been at the heart of much eighteenth-century chemistry, and the work of Berzelius helped to ensure that it remained central in the first half of the nineteenth century. Quantitative analysis, using the balance to establish the weight of each constituent, went along with qualitative analysis, the identification of particular constituents (metals, acids, alkalis, etc.) using the blowpipe and other tests. These analyses, combined with an atomic theory, enabled Berzelius to write formulas for the precise composition of many substances, using chemical symbols that he invented. His formulas, and the symbols on which he based them, were so prominent a part of his influential and widely translated textbooks that they helped to shape the whole of chemical discourse. There were problems, as we shall see later, in establishing these formulas, problems of the kind created by Dalton through the application of *his* simplicity criteria. Still, Berzelius's formulas represented a triumph of analysis and classification. The consistent use of formulas was subsequently incorporated in the writing of chemical equations to show the course of a reaction; chemical equations came into general use around 1835.

Berzelius's methodology had been derived from inorganic chemistry, and especially the chemistry of salts, and it was based on atomism and electrochemical dualism. It was remarkably successful in giving inorganic chemistry coherent shape, with formulas, affinities, and classification firmly in place. But inorganic chemistry, the chemistry that included salts and minerals, was much more easily handled than organic chemistry, the chemistry of those compound substances that exist in nature as constituents of animals or plants, or are derived from such constituents. The next chapter will explore problems and triumphs in the establishment of organic chemistry.