2. From Alchemy to Chemistry

The Four Elements

In early days it was thought that there were four elements. Ancient philosophers chose four substances among everything around them as something special: these were the 'elements' that constituted the whole universe.

The idea of elements goes back to Empedocles of Sicily in the fifth century B.C., who called them 'roots.' According to Empedocles, the building blocks of the universe were fire, water, earth and air. Everything else could be broken into some combination of these roots, but the roots could not be split into anything simpler than what they were. A root substance contained itself, only itself, and nothing but itself.

For example, fire could not be divided into anything else, or, air, for that matter. But other material could be broken into these 'roots' in some proportion or other. As an example, Empedocles offered to explain how bones came into being: "[T]he kindly earth received in its broad hollows of the eight parts two of the brightness of [water], and four of [fire], and these came to be white bones, marvelously held together by the gluing of harmony."[1] The essential idea was that nothing new could come into being in our world. Things came to be or passed away because roots combined to form them, or separated to destroy them. As Empedocles put it: "Fools—for they have no far-reaching thoughts—who suppose that that which was not before comes into being or that anything perishes and is utterly destroyed."[2]

There is an interesting legend about how Empedocles died. He threw himself into a volcano on Mount Etna in Sicily in 430 B.C. Some say he did it to prove he was immortal, thinking the 'roots' in his body could not be 'utterly destroyed,' that he would return to Earth in some other form. No one can find out now what he was thinking when he took the plunge, but the words of the poet Mat-

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thew Arnold in the poem "Empedocles on Etna" probably give us an idea: "To the elements it came from/everything will return./Our bodies to earth/our blood to water/heat to fire,/breath to air."

Empedocles' idea of elements have ruled our thoughts ever since. The list of elements may have increased, but the basic idea has remained more or less the same. Later philosophers expanded on Empedocles' idea of roots. Plato named them 'elements' (*stoicheion* in Greek, which means 'the first things') and went on to devise a theory of particles, or atoms, which constituted these elements.

Not only chemists but physicians also found a use for the idea of elements. They thought these elements could help them interpret diseases. Hippocrates imagined that there were four basic fluids, or 'humors,' in the body, and all illness came about as a result of some imbalance between these four humors. The four humors were blood, black bile, yellow bile and phlegm. These were related to the Empedoclean roots—earth with black bile, fire with yellow bile, water with phlegm, and all four of them with blood. The basic idea of curing a disease for Hippocrates was to restore the balance of fluids.

A century after Empedocles' death, Plato's student Aristotle added a fifth element to the list, which he called quintessence, the fifth 'essence.' He argued that heavenly bodies could not be made of lowly things on Earth, although he had no persuasive arguments to support his idea. But one did not need experimental proofs in those days. Therefore, according to Aristotle, celestial objects were made of something more pure than our earthly four elements. It took almost two millennia until Galileo Galilei countered Aristotle's argument by showing pockmarks on the surface of the Moon and black spots in the Sun, thereby proving that heavenly objects were probably not different from earthly things.

Aristotle also came up with a philosophy of dynamics based on these elements. He claimed that the four elements moved along straight lines, and they had a unique direction of motion. Fire and air tended to go up, whereas water and earth moved down until they reached what he called their 'natural places.' A stone fell to the ground because in terms of basic elements a stone was mostly made of earth. Smoke went up in the air because it was mostly made of air and fire, and it moved up and away from earth and water. So elements not only constituted the universe, they also determined how they would move.

The Emergence of Alchemy

Aristotle had another idea that set a group of people on a path that would ultimately end up as modern chemistry. He thought that everything had a *potential* that it would eventually reveal unless inhibited from doing so. A seed was therefore potentially a plant, and would grow into one unless hindered. This was also true for physical objects—they moved from one place to another to achieve their potential, which was how Aristotle explained the motion of objects. Things fell down to Earth because it was natural for them to do so in order to achieve their potential.

This may sound like mumbo-jumbo to us now, but these ideas ruled for centuries. The idea of the inner potential of things also implied that they could be *changed* from one to another. This gave the idea that perhaps even things such as lead could be changed to gold—there was nothing in the Aristotelian philosophy that specifically prohibited this type of change. And so alchemy was born, with the dream of finding the 'philosopher's stone' that would turn a 'lower' (or base) metal into 'incorruptible' gold.

Alchemy essentially led nowhere, but it produced side alleys that led to the understanding of basic chemistry. If one picks up a modern chemistry book today and chooses a word at random describing some chemical process or substance, the chances are that the word would date back the days of alchemy. For example, the word 'gas' was used in the context of chemical experiments in 1648 in the last days of alchemy, replacing the old word 'spirit,' by an alchemist named Jan Baptist van Helmont. And the same goes for many chemical apparatuses and laboratory tools used today.

Alchemists were content with the idea of four elements for more than a thousand years, until Paracelsus added three more to the list in the sixteenth century. He believed that apart from the four elements, there was another level in the hierarchy of substances in the universe, which contained three more elements: salt, mercury and sulfur. These three things ('tria prima') apparently gave every substance its inner essence and form.

The definition of these three extra elements, however, was confusing. They were believed to be more like principles than actual substances. To add to the confusion, Paracelsus also held that "there are many sulphurs, salts, and mercuries of gold—according to the many kinds of gold that exist. The same is true of other metals, of plants, fruit, animals and men."[3]

Such vague statements gave rise to chaos among the scholars, and they began to use these ideas liberally, as they saw fit. An English alchemist by the name of Thomas Moffett complained in 1554: "Some wish that there should be one element, while others think they are many, and some even think they are infinite, innumerable, and immovable; these assert there are two, those three, some others say four, while others demand eight."[4] Some philosophers even went as far as connecting these three principles with the Holy Trinity in Christian theology.[5]

A century later, Johann Joachim Becher criticized the lack of consensus among alchemists regarding the identity of elements in his popular book *Oedipus Chemicus* (1664). At the same time, there were also chemists such as Michael Sendivogius who suggested (in 1604, in his *New Light of Alchymy*) that the study of elements was futile because only God could create from them: "If therefore thou canst out of the Elements produce nothing but these three Principles, wherefore then is that vain labour of thine to seek after, or to endeavour to make that which Nature hath already made to thy hands? Is it not better to go three mile then [sic] four? Let it suffice then to have three Principles, out of which Nature doth produce all things in the Earth, and upon the Earth; which three we find to be entirely in every thing."[6]

Chaos like this usually gives rise to paradigm shifts in science. It was not long until scholars began to question the whole idea of four elements. The first blow to the ancient view of four elements came from Robert Boyle, a British scientist, in his *A Sceptical Chymist* (1661), a book that he wrote in the form of a dialog, much in the style of Galileo Galilei, whom he had a chance to meet and whom he admired.

Boyle claimed that belief in the Aristotelian elements was based on insufficient evidence. He criticized the generalists among alchemists, saying that they had very little knowledge of the elements, and that they employed experiments "rather to illustrate than to demonstrate their Doctrines."[7] It was impossible, he reasoned, to form any substance from the four Greek elements, and also to extract these elements from any substance. He wrote that "there [was] not any certain and determinate number of such Principles or Elements to be met with Universally in mixt bodies." By 'mixt' bodies he meant objects made of simple elements, or what we now call compounds. He took each of the so-called Principles or Elements (such as salt and sulfur) and showed that their elemental nature was untenable.

Boyle also questioned the Paracelsian doctrine that fire separated the elements from a mixt body. He wondered how an alchemist would categorize glass since "It is not destroyed but produced by the action of fire." Also, he deplored the vague statements to the effect that quality of matter such as color depended on its elements. Color, he insisted, came from the breaking up of light by its passage through a colored object, and had nothing to do with elements. (He would be refuted after two centuries, and identifying elements through colors or spectrum would one day lead to the discovery of helium.) However, by insisting on experimental evidence, Boyle's words ushered in a change in the outlook of chemical sciences, just as Galileo's books did for physics.

Boyle's book ended with a note of dissatisfaction, and did not really contain any alternative ideas of elements that could be tested with experiments. There was a hint in his book, though, that chemical changes were probably best understood in terms of atoms. But the major point of his critique of chemistry was that chemists should make measurement of the substances they were experimenting with. Without measurements, chemistry would be reduced to sheer magic.

Fortunately, his call to experimental chemists did not go unheeded. Soon after Boyle's era, chemists began to track chemical changes of substances by the changes in their weight. The use of balance in studying chemistry brought about a revolution of sorts.

The rapid progress in chemistry also changed the ideas of elements. How elemental were the elements, chemists had begun to ask. By the end of eighteenth century, chemists had realized

Fig. 2.1 French stamp honoring Lavoisier, issued in 1943

that 'air' was not a single element. They had discovered different kinds of 'air,' including an 'inflammable air' that we now know as hydrogen, or 'mephitic air' that is nothing but nitrogen. In 1774, Joseph Priestley, a British chemist, was able to isolate a kind of 'air' that was responsible for combustion that was named 'oxygen' by Antoine Lavoisier, a French chemist (Fig. 2.1). Lavoisier went on to prove that water was made of two 'airs' that we now know as hydrogen and oxygen.

Lavoisier further pushed the concept of weight changes in the case of interpreting chemical reaction, and he connected the idea of weight of substances to elements. He insisted that the weight of an element should not change in a reaction. If it did, it should not to be considered an element. "We must always suppose an exact equality between the elements of the body examined and those of the product of its analysis," he declared.[8] Laviosier's insistence on measuring weight took chemistry forward by leaps and bounds. Quantitative chemistry was born, and the law of combining weights was discovered.

These ideas blew apart the last bastions of the ancient philosophical system. Did fire have weight? Lavoisier contended that it did not. Fire simply was a phenomenon that accompanied combustion. So he claimed it was *not* an element. On the other hand, he thought heat was a substance with weight (calorie) that flowed out of matter that was cooling. In 1789, he put forward a list of thirty-three "simple substances belonging to all kingdoms of nature, which may be considered as the elements of bodies." The list included oxygen and hydrogen but also included things such as light and heat.

Chemistry Goes Electric

Around this time, physicists discovered a new tool that could help chemists in their experiments. For the first time chemists brought into their laboratory something completely different from what ancient alchemists had used. It was electricity. Alessandro Volta found in 1800 a method of sustaining electrical current by putting two different metals in contact. He made a 'pile' of alternating silver and zinc plates immersed in saltwater, and came up with the first electric cell.

The same year, William Nicholson and Anthony Carlisle replicated Volta's experiments in England. During one of their experiments with the Voltaic pile, Nicholson happened to put drops of water near the wire that entered the top of the metallic pile. They were surprised to see a gas bubble out of water when electricity passed through it. Pursuing the matter, they discovered that electricity decomposed water into hydrogen and oxygen, the constituent elements of water as discovered by Lavoisier. They had discovered electrolysis, a way of breaking up compounds into their simpler constituents.

Within a few years, Humphry Davy of England found he could decompose many other chemical substances into simpler elements. In 1807 he passed electricity through caustic potash and isolated potassium, the first metal to be separated by electrolysis. He described potassium as a metal that, when thrown into water, "skimmed about excitedly with a hissing sound, and soon burned with a lovely lavender light."[9] Afterwards he was able to separate another metal, sodium, by passing an electric current through sodium hydroxide.

This was a major achievement indeed because ancient alchemists had always confused sodium with potassium. It was only in the seventeenth century that they realized there were differences between potassium carbonate (potash, or 'vegetable alkali') and sodium carbonate (soda, or 'mineral alkali'); one came from the ashes of plants while the other came from rocks, and hence the difference in their names. But often alchemists could not tell one from the other. Davy's experiments showed the power of electrolysis for the study of chemistry. Soon he was able to discover calcium, magnesium, boron and barium. The list of elements was now burgeoning.

Then Davy met with an accident in 1813 while experimenting with a dangerous substance called nitrogen trichloride, and he lost his eyesight. To continue with his experiments, he hired an assistant who would go on to revolutionize the study of electricity. This assistant, Michael Faraday, helped Davy with his electrolysis experiments and discovered that the weights of material separated by electricity depended on the amount of electrical current passing through it. It was in a way a continuation of the experimental philosophy of Lavoisier, by insisting on a quantitative measure of the reactions in determining the elemental nature of objects.

Careful weight experiments showed an interesting result. Elements had weights that were multiples of the weight of hydrogen. Oxygen, for example, was roughly 16 times heavier than hydrogen, whereas nitrogen was 14 times as heavy. This observation led to a modern definition of elements, as a substance whose combining weight was one particular number or some multiple of that number. The fundamental unit of chemical weight was the weight of hydrogen. Everything was measured in terms of the weight of hydrogen.

This led chemists to think that hydrogen was the simplest of all elements. So the idea of a 'structure' of matter was born: hydrogen had a simple structure and other elements had a more complicated structure. Perhaps the building blocks of matter were not elements but something more fundamental. Greek philosophers had of course thought of such tiny building blocks of matter: atoms. Nineteenth-century chemists revived the idea of atoms in a modern form. John Dalton of England came up with a theory of atomic structure in 1808 in his book *New System of Chemical Philosophy,* in which he had a list of thirty-six elements.

Within five years, this list was expanded by a Swedish chemist named Jöns Jacob Berzelius to accommodate forty-seven elements. He also came up with symbols for the elements that chemists use to this day, for example, S for sulfur and O for oxygen, and so on.

By 1830, fifty-five elements of nature had been identified through chemical or electrochemical means. Chemists began to wonder at this point if there were more such elements, or if they had found them all. They also wondered why there were so many elements.

Just around this time a startling development changed the face of chemistry. Chemists had benefitted earlier from using tools of physics such as electricity, and it would prove advantageous to them yet again. This time they used the tools that physicists had reserved for studying light. A new era would dawn in chemistry when chemists started using light to study matter.

The introduction of light to chemistry would also bring astronomers into the game of element hunting.

NOTES

1. From 'The fragments of Empedocles,' Fr. 96, as quoted in *Routledge History of Philosophy,* Vol. 1. 'From the beginning to Plato,' ed. C. C. Whiston (Routledge, London; 1997), 188.
2. As quoted in J. Longrigg, "The Roots of all things", *Isis,* Vol. 67 (1976), 421.
3. W. Pagel, *Paracelsus: An Introduction to Philosophical Medicine in the Era of Renaissance* (Karger: New York,1982, 2nd Ed.), 103.
4. Allen G. Debus, *The English Paracelsians* (Oldbourne: London, 1965), 71–76.
5. Allen G. Debus, The Chemical Philosophy (Dover, New York: 2002), 79.
6. Ibid., 84.
7. Ibid., 482.
8. Gerald J. Holton, Introduction to Concepts and Theories in Physical Sciences (Princeton University Press: Princeton, 1985), 231.
9. Mary E. Weeks, "The discovery of the elements. IX. Three alkali metals: Potassium, sodium, and lithium," *Journal of Chemical Education*, Vol. 9 (6) (1932), 1035.

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