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ГОСУДАРСТВЕННОЕ ОБРАЗОВАТЕЛЬНОЕ УЧРЕЖДЕНИЕ  
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## **A BRIEF HISTORY OF SCIENCE**

*Рекомендовано Редакционно-издательским советом  
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Сборник включает 16 текстов, заимствованных из современной научной английской литературы. Он содержит глоссарий, дающий образцы английской терминологии, и рекомендации, которые могут быть полезны для грамотного составления пересказов. В конце имеется список литературы, рекомендованной студентам для дальнейшей самостоятельной работы с оригинальной литературой по специальности.

Цель сборника – формирование умений и навыков чтения и понимания научно-технических текстов по специальности, аннотирования и реферирования читаемой литературы, а также развитие дальнейшего познавательного интереса в рамках изучаемой науки.

Рекомендуется студентам химического факультета в качестве дополнения к основному учебнику, а также может быть полезен студентам, обучающимся по программе «Переводчик в сфере профессиональной коммуникации».

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### *Методические указания*

Сборник *A Brief History of Science* составлен на основе оригинальных текстов научной проблематики, представляющих несомненный практический интерес для студентов. В качестве источников использованы популярные американские и английские издания. Тематика материала отобрана с учётом уже полученных студентами знаний в области химии и истории развития научного знания. При подборе текстов автор ориентировался, прежде всего, на лексику, необходимую для дальнейшей работы учащихся над литературой по специальности с учётом словарного запаса, приобретенного на начальном этапе изучения языка.

Материал сборника предусматривает формирование у студентов умений и навыков, дающих возможность перейти к чтению оригинальной иностранной литературы по широкому химическому профилю. Тексты сборника имеют различный уровень сложности и могут быть использованы для совершенствования навыков реферирования.

I раздел сборника посвящён научным достижениям 17-20 веков в области химии.

Во II разделе освещаются отдельно взятые открытия выдающихся учёных (Менделеева, Дальтона, Фарадея, Кюри).

В III разделе приводится глоссарий, необходимый для понимания научной терминологии отобранных текстов. В конце раздела даются выражения для составления аннотаций и рефератов, также указываются источники, рекомендованные для дальнейшего самостоятельного чтения оригинальных популярных изданий, представляющих интерес для тех, кто решит продолжить своё обучение в аспирантуре.

The search for knowledge forms a key part of the human quest for life in all its fullness. And *A Brief History Of Science* – is an attempt to give an overview of the bewilderingly immense history of scientific advances in chemistry. This book surveys the rise of chemistry and its main developments over the past centuries.

## PART I

### Premodern chemistry

CHEMISTRY AS the science of matter in all its forms and transformations goes back to prehistory. Humans, unwittingly, have always been both proactive chemists and observers of spontaneous chemical processes, such as combustion and fermentation, in everyday life. Cooking, firing pottery, making metal alloys, mixing paints and dyes, concocting medicines and poisons, producing adhesives, and blending floral essences into perfumes are all chemical processes.

Although, in the course of several millennia, humankind became increasingly skilful in all these matters, the knowledge applied was the product over long periods of time of trial and error. Such principles as there were (and in some fields they were well entrenched) rested on concepts of the basic constituents of matter, which, for some two to three centuries, we have known to be totally erroneous. The science defined by these principles is known as alchemy, and, until about the mid-eighteenth century, all chemistry was alchemy - that is, it was totally unscientific by modern standards.

Paradoxically, for almost the whole of the seventeenth and eighteenth centuries, Newtonian physics and alchemy existed side by side. Newton himself was a dedicated alchemist, carrying out any number of failed experiments from the laboratory he had set up in Trinity College, Cambridge. Newton's contemporary, Robert Boyle (1627-91), tried to put the shop in order, and in *The Sceptical Chymist* (published in 1661) attacked both alchemical principles and Aristotle's four-element theory, based on earth, water, air and fire. Although he proposed, as an alternative, other simple and primitive elements, he came nowhere near analytical chemistry, as it began to evolve in the eighteenth century.

As a physicist, Boyle achieved notable results with gases and developed a versatile new air pump. But he never came close to a correct understanding of the gaseous state of matter, which in the eighteenth century, with

men such as Joseph Priestley (1733-1804) and Antoine Lavoisier (1743-94), unlocked the door to modern chemistry as we know it.

Before looking at this new world, two points are worth making about chemistry, or alchemy, at any stage of history. The first is that the phenomena that are their concern are pre-eminently earth-bound. The world, as experienced by humans, is characterised by the solid, liquid and gaseous states of matter, and the capacity of one to transform into another, with or without human intervention. Such transformations belong to the wide class of chemical reactions, which largely define the subject.

The second point is that chemistry, even at its most esoteric, is inherently useful to humankind. This remains true when its ends are destructive, as they are in the development of explosives. The result has often been that chemists turn their skills to profitable enterprise. Ludwig Mond (1839-1909), who started life in Germany as a very competent chemist, ended up in England as one of the founders of Imperial Chemical Industries, whose success was based on the new methods he developed for producing ammonia and soda - two chemicals with wide industrial applications. None of this would have been possible without the eighteenth-century revolution in chemistry. This then is where the story begins.

### **Lavoisier: father of chemistry**

Antoine Lavoisier (1743-94), rightly regarded as the father of modern chemistry, is important not only for his own original discoveries but also for providing the best possible framework for those of his contemporaries. In particular he was the first to establish the true nature of fire, although the experimental results that enabled him to do so were not his own. Lavoisier, with insights that others lacked, realized the true significance of chemical research carried out in the second half of the eighteenth century, not only in France, but also in England and Sweden. The essential focus of this research was air, and how it responded to various processes, notably heating. Air and fire were two of the four elements, since antiquity accepted as the fundamental constituents of all matter on earth.

In the eighteenth century, chemistry was the focus of a revolution in science. The century got off to a false start when the phlogiston theory of combustion, developed by the German chemist Georg Stahl (1660-1734), came to be the accepted explanation of all reactions involving heat and fire. Phlogiston was a vital essence thought to be present in all combustible substances, which was lost as they burn. This loss then explained not only the transformation of the substance itself, but that of the air around it. In a fire, wood lost phlogiston as it burnt to cinders, and air gained it, with notable changes in its properties - but not so that it ceased to be air. In the course of the eighteenth century, chemists were ingenious in incorporating phlogiston into the results

of their experiments, even though their cumulative effect made the truth of Stahl's theory ever more improbable. Lavoisier, by showing that phlogiston was not needed to explain the results of the experiments, initiated the breakthrough into chemistry as we know it today.

Lavoisier, although born into a household that was prosperous and well connected, grew up in a family which stressed both ambition and caution. Lavoisier would prove to have too much of the former, and too little of the latter. As the only son to live beyond childhood it was natural that he should train as a lawyer, the accepted way to power and influence, but his interests were always in science. From a very early age his strategy was to look for offices and employment in which the opportunity to practise science would combine with material rewards sufficient to cover the costs of doing so. For someone dedicated to experiment, these could be considerable. In eighteenth-century France, however, Lavoisier's favoured strategy could only succeed if full account was taken of political reality. In the first forty-odd years of Lavoisier's life this meant not only accepting the dictates of a centralised state, in which the king was the ultimate source of power and patronage, but also advancing its interests.

Lavoisier, although always committed to improving public life in France, was still subject to the limitations of government, such as they were in prerevolutionary France, and these were critical in determining the course of his life. So much so, that when the revolution came, Lavoisier paid for his adherence to the ancien regime with his life.

In 1760, Lavoisier, aged seventeen, after a brilliant school career, enrolled in the University of Paris to study mathematics and philosophy. After a year, however, he switched to a three-year law course, but without abandoning his scientific interests. He attended public lectures, took private courses, and carried out fieldwork. Given the man he was, one of his ambitions, even at this early stage, was to be elected to the Academic des Sciences. Considering that the Academy had only fifty-four members, divided between six different sciences, with new elections dependent on a vacancy occurring, Lavoisier was certainly ambitious for a man in his twenties. None the less, he worked out a two-pronged strategy that brought him success when he was only twenty-five.

First, with royal permission, Lavoisier's entry in a competition for the best way of lighting the streets of Paris was awarded a special gold medal by the Academy. Second, with his sights set on chemistry - one of the six recognised sciences - Lavoisier presented two papers on the analysis of gypsum.

Scientifically these were boldly innovative. There were two recognised ways of chemical analysis, the wet and the dry. The latter, now known as destructive analysis by heat, was standard in eighteenth-century chemistry. Lavoisier applied it also to discover that gypsum, when heated, lost a quarter of its weight in a vapour that proved to be pure water. The process could then be reversed, with the water added back, to restore the original state. This, the

wet way, now known as solvent analysis, showed that gypsum was 'a true neutral salt that becomes a solid by fixing water and forming crystals'. This property made gypsum the ideal material for casts for setting broken bones: this is the original plaster of Paris, which has only recently given away to fibreglass in orthopaedic surgery.

Lavoisier wrote up his experiments with gypsum in two papers read to the Academy in 1765 and 1766. Shortly after the second paper there was a vacancy for an adjunct (the lowest rank) in chemistry, but Lavoisier, although strongly supported and placed on the short list, was not elected. Never a man to give up, Lavoisier continued along the experimental path, by researching techniques for determining the specific weights of liquids. This means finding out the weight of a liquid in comparison with that of water in standard conditions: he worked with hydrometers, instruments made in two forms, variable immersion and constant immersion. (The former is familiar in the form used by garages to measure the acidity of car batteries.)

This work supplemented the results that Lavoisier had already obtained with chemical balances and, as always, his extremely high standards of accuracy produced important new results. These related particularly to measuring acidity in the light of Lavoisier's hypothesis that it was caused by a single element. Once again papers were read before the Academy in the early months of 1768. There was again a vacancy for an adjunct chemist, and this time Lavoisier achieved a majority of votes. Appointment was, however, the prerogative of the king, who, although nominating another candidate on the grounds of seniority and service to the state - also allowed Lavoisier in as a supernumerary adjunct. On 1 June 1768 he was formally installed as a member.

Anticipating not only his election but also the prospective costs of continuing his experiments, Lavoisier was to take a step early in 1768 that he would later pay for with his life. His grandmother had died in January and, following advice from a family friend, he invested a considerable legacy in a share in the royal Tax Farm. Under the French monarchy this would ensure him a substantial revenue from commissions for collecting tax - an activity supported with all the power of the state. Given that popular discontent in France was largely caused by harsh and unjust taxes, Lavoisier had, unwittingly, allowed himself to become a considerable hostage to fortune. As a member of the Academy, with a strong record of service to the state, all this - in a time without tabloid newspapers - did not count for much in Lavoisier's circles.

For twenty years and more, the young academician would continue his researches, combining them with a succession of science-related public appointments. Lavoisier was progressive in that almost everything he did in the public sphere was focused on using the French national resources, often in a state of extreme neglect, more efficiently. His work extended far outside Paris, so he was often travelling, and in a countryside where long - held special inter-

ests could block any reform, he still achieved a great deal. At the same time Lavoisier continued with experiment and publication. The direction he was moving in was to establish the properties of air as fundamental to chemistry, a subject which, when he had first looked at it in the early 1760s, he found to be composed of absolutely incoherent ideas and unproven suppositions... with no method of instruction, and... untouched by the logic of science'. The phenomenon at the centre of his research was simple, although it had been little noted. Iron and copper exposed to air change into powdery substances, rust and verdigris, at the same time increasing in weight. By this process air was fixed in a solid metallic compound.

Lavoisier also found that production of sulphuric acid, made by mixing burnt sulphur with water, involved a similar weight gain. The same result could be achieved with phosphorus. The only explanation was that in the process of burning, air was once again fixed in the element. Believing this 'air' to be a universal constituent of acids, he coined the term 'oxygene', from the Greek *oxys*, meaning 'acidic'. In this he was mistaken: we now know that not all acids (hydrochloric, for example) contain oxygen. Oxygen was first discovered by Joseph Priestley (1733-1804), as Lavoisier acknowledged, but this was just another case of British discovery and French explanation. Lavoisier was then able to summarise his results in general terms:

*Air exists in two modes in nature. Sometimes it appears as a highly attenuated, highly dilated, and highly elastic fluid, such as the one we breathe. At other times it is fixed in substances and combines intimately with them, losing all its previous properties. Air in this state is no longer fluid but rather becomes solid, and it can only regain its fluidity if the substance with which it is combined is destroyed.*

This analysis still fails to get to terms with the complexity of air as it exists in nature. The atmosphere around us provides us with a mixture of oxygen and nitrogen, from which animal organisms derive the oxygen necessary for sustaining life. It also contains carbon dioxide, essential for plant life, but with the supply continuously replenished by animal respiration.

Carbon dioxide ( $\text{CO}_2$ ), produced by reacting sulphuric acid with chalk, was described by Joseph Black (1728-99) in 1754, so that this 'fixed air' became the first of the gases to be examined chemically. Black produced it by heating limestone, and showed that it supported neither life nor combustion. The existence of gases other than air was thus demonstrated for the first time, but it would take many years before the full implications were appreciated – a process in which Lavoisier would play a key role.

In 1772 Paris learnt that Priestley in England had succeeded in fixing this new 'air' in water. By a somewhat complicated process of reasoning, this led Lavoisier to use the Academy's giant focusing lens to see what happened to a diamond when heated in an evacuated chamber. The fact that a reaction took place, but without combustion (which is what he expected), led him to



search for a general explanation as to why 'a flame, but not concentrated sunlight, will ignite inflammable substances'. Before his explanation could become complete, there was much ground to cover.

In 1766, the English chemist, Henry Cavendish (1731-1810), investigating the 'factitious airs' which made up the earth's atmosphere, isolated hydrogen. He named it 'inflammable air', identifying it with phlogiston because of its power to react in almost spontaneous combustion. In 1783, Lavoisier, working with Pierre Simon de Laplace (1749-1827) - later to be well known in mathematical physics - turned his experiments to 'inflammable air' (produced by reacting iron with sulphuric acid). These culminated in a demonstration that inflammable air and vital air, burnt together, form water. (A year later, in 1784, Cavendish achieved the same result by using an electric spark to explode hydrogen.) For the first time water was proved to be not an element but a compound, a discovery that would open the way to a 'revolutionary new set of chemical theories'. In the same year, 1783, the Montgolfier brothers successfully launched the first hot-air balloon. Lavoisier realised immediately that hydrogen could fill balloons with something much lighter than hot air - an insight with fateful consequences for travel by airship in the twentieth century.

In November 1774, Priestley visited Paris and told Lavoisier of the remarkable properties of the 'air' released by heating, intensely, the red precipitate of mercury (a so-called calx produced by heating, moderately, metallic mercury). Lavoisier, investigating 'air' produced in this way, found that it supported both respiration and combustion much better than ordinary atmospheric air. The conclusion he came to was that 'the air we breathe contains only one quarter true air', the rest, which is non-respirable, proved to be nitrogen, identified by Priestley as one of the two constituents of ammonia, the other being hydrogen. Ammonia is itself a gas, which Priestley discovered by heating its natural salts in a retort (a process which led to the discovery of a number of other gases - notably nitrous oxide, commonly known as 'laughing gas'). The path of experiment then led Lavoisier to separate atmospheric air into its salubrious and mephitic parts. The former category consisted simply of oxygen, while the latter subdivided into mephitic air produced by respiration (that is, carbon dioxide), and the non-respirable portion of the atmosphere (named 'mofette' by Lavoisier).

Lavoisier also used results from experiments conducted by Priestley and presented to the Royal Society in London to explain the role of oxygen in respiration. To support his conclusion that respiration is combustion in the lungs, he noted that both blood and the oxides of metals such as mercury, lead and iron, are coloured red. Finally, on 12 November 1777, he presented to the Academy his *Memoir on the General Nature of Combustion* (which did, however, note that further experiments were still necessary). None the less the paper put forward 'a hypothesis that explains in a highly satisfactory manner

all the phenomena of combustion, calcination, and even, in part, those that accompany the respiration of animals'.

Lavoisier then proceeded to dispense with phlogiston, putting his own alternative explanation:

*The matter of fire or light is a very subtle and very elastic fluid that surrounds all parts of the planet we live on, which penetrates with greater ease all the bodies of which it is composed, and which tends, when free, to distribute itself uniformly in everything... this fluid dissolves a great many bodies,... it combines with them the same way that water combines with salts and acids combine with metals... the bodies so combined and dissolved in fluid fire lose some of the properties they had before the combination and acquire new ones that make them more like the matter of fire.*

With the benefit of hindsight, this is all very unsatisfactory: Lavoisier was out of the frying-pan into the fire. Equating fire with light was certainly an advance, but Lavoisier plainly failed to view fire from the perspective of a violent reaction between oxygen and some combustible material. Lavoisier may have banished phlogiston, but caloric, which he put in its place, raised more problems than it solved.

Fire appears as both cause and effect of the reactions to which it belongs. Lavoisier failed, however, to realise that it was essentially a by-product, made observable by incandescence. This can hardly be held against him, since the basic physics was unknown until the second half of the nineteenth century.

When revolution came to France, Lavoisier continued to be a dominant in the world of science and played an important part in establishing a standard international system of weights and measures. None the less, he had been a tax farmer under the *ancien regime*, and as such he was, with all others in the same category, condemned to the guillotine in 1794. The loss to science of a man at the height of his powers was incalculable. As his contemporary the mathematician Joseph Louis Lagrange (1736-1813) said, 'It took only a moment to sever his head, and probably one hundred years will not suffice to produce another like it.' With this brutal departure, it is now time to see what *la perfide Albion*, safe from revolution, had to contribute to chemistry.

## Humphry Davy

When Sir Humphry was chosen as the subject of one of E. C. Bentley's clerihews, his name was well known in Britain, where schools taught that the invention of the miner's safety lamp made him one of humankind's great benefactors. All this was some time in the first half of the twentieth century, when coal-mining was still important in the British economy. At the beginning of the nineteenth century, he was even more famous, being the first scientist since Newton to be honoured with a knighthood. If today, he is largely forgotten, his discovery of sodium remains an important milestone in the history of chemistry. This was but one of his achievements. Before looking at what this all meant, it is best to look at the man himself.

Humphry Davy was born in Penzance, at the furthest end of Cornwall, in 1778. The county was known for its shipwrecks, tin-mines and mild winter climate - all factors that would play a role in Davy's early life. Although apprenticed as a youth to a surgeon apothecary (with the prospect of a good career), Davy's interests were always wide-ranging. He loved being outside, particularly for fishing and shooting, but he also studied philosophy and history, and his talents as a poet (which he never lost) later earned him the friendship of Wordsworth and Coleridge.

Davy's interest in science was stimulated by a shipwrecked French surgeon, who encouraged him to experiment and also introduced him to Lavoisier's *Elements de chimie*.

At much the same time, James Watt, whose invention of an efficient steam pump had transformed Cornish mining, sent his tubercular son Gregory to lodge with the Davy family, to benefit from the Cornish climate. Thomas Wedgwood, son of Josiah, the famous potter, also came to Penzance for his health. In such company, Davy found not only an audience for his own scientific ideas, but also gained an entree to the Lunar Society of Birmingham, whose members combined wealth and influence with a devotion to scientific discovery.

In 1798, Thomas Beddoes, noted for relating chemistry to medicine (in which he advocated the wide use of opium), was another visitor to Cornwall, where Gregory Watt acquainted him with experiments on heat and light carried out by Davy. Beddoes was so impressed that he arranged for the results, later repudiated by Davy, to be published. Beddoes went much further. Helped by funding from the Wedgwoods, he established the Pneumatic Institution (a scientific think-tank *avant la lettre*) in his own house in Bristol and appointed Davy as his assistant.

In Bristol Davy experimented, sometimes dangerously, with various gases, discovering that nitrous oxide ( $N_2O$ ), popularly known as 'laughing gas', could be used as an anaesthetic. This work, combined with researches into carbon dioxide, which nearly ended his life, led him to conclude that

'chemical properties clearly did not depend in any simple way on material compositions' a counter-intuitive principle that no prospective chemist should ignore. At the age of twenty-one Davy was, in the year 1799, already a man to be reckoned with. In this same year the world of science was to witness two important but unrelated events, which in combination would determine the future direction of Davy's life.

### **The electrochemical breakthrough**

The first of these was the invention of Alessandro Volta's (1745-1827) pile. Although the commercial future of electricity never occurred to Davy and his contemporaries, the scientific possibilities of Volta's pile became immediately apparent. When Volta's paper reporting his discovery was received by the Royal Society in 1799, the two referees found that the electric current could be used to decompose water. Davy, working with a battery of 110 double plates provided by Beddoes, found that it would not work with pure water as the electrolyte. On the other hand, nitric acid was extremely effective.

Davy also found that the copper electrode could be replaced with charcoal. (Graphite, another form of carbon, is still used in electrodes.) Davy, noting that the zinc electrode oxidised in the process of use, concluded that the current was produced by a chemical reaction: contrary to Volta's view, mere contact was not sufficient. This was a key insight, since it opened the way to reversing the process, that is, using a current to cause a reaction.

The result was the electrolytic cell. The basic model with two electrodes separated by an electrolyte was the same, but a current from an outside source was then to be passed through the cell to see what reactions would occur. The possibilities were immense and went further than Davy could possibly have conceived of. Any number of substances could be chosen both for the electrodes and for the electrolyte. Useful reactions proved to need considerable electric power, which explains the vast battery provided by Beddoes. Even this was not enough for Davy, and it was in London, not Bristol, that his major discoveries based on electrolysis would be made.

This brings us to the second key event of the year 1799, the founding of the Royal Institution by Count Rumford. The object was to encourage and popularise the application of scientific principles. Ever restless, Rumford only stayed three years in London, moving in 1802 to Paris, where he married Lavoisier's widow (who was not nearly so happy with him as she had been with her first husband). Even so, he did bring Davy to London, and by doing so initiated one of the most remarkable eras in the history of science.

Davy became lecturer in chemistry at the Royal Institution in 1801, professor in 1802, Fellow of the Royal Society in 1803, and one of the two secretaries in 1807 - all before he was thirty. The Royal Institution provided him

with a magnificent laboratory, and a lecture hall where not only scientists, but London society, came to see him demonstrate the work in progress. He was a born showman, and a society lady attending one of his lectures noted, 'those eyes were made for something besides poring over crucibles'.

The climax to Davy's work during his early years at the Royal Institution came with his Bakerian lecture, delivered on 20 November 1806. There he described his demonstration of how an electric current passed through pure water produces nothing but hydrogen and oxygen. To achieve this result he worked with an electrolytic cell made of agate and gold and with pure water from a silver still. His battery had 100 double plates of copper and zinc, and the experiment ran for 24 hours. Count Rumford had certainly left the Royal Institution well endowed.

The decomposition of water was decisive in proving that electrolysis could proceed without requiring or producing any acid or alkali. Davy, taking over from Lavoisier, had established chemistry as much an English as a French science. The Institut de Paris awarded him a prize for the best work on electricity, which, on the instructions of Napoleon, was open to the citizens of any nation remarkably broad-minded seeing what the British had done to Napoleon at Trafalgar.

At the end of his Bakerian lecture, Davy revealed how the chemical properties of metals could depend upon their electrical state. In his electrolytic cell positively charged silver had proved to be reactive, and so converted to silver oxide, and negatively charged zinc, a metal higher in the reactivity series, inert. According to his final summary,

*Amongst the substances that combine chemically, all those, the electrical energies of which are well known, exhibit opposite states... supposing perfect freedom of motion in their particles or elementary matter, they ought, according to the principles laid down, to attract each other in consequence of their electrical powers.*

In other words, molecules were bound together by electrical forces. This was, effectively, the beginning of electrochemistry a field with immense potential, which Davy himself began to realise almost immediately.

In 1807 Davy was invited once again to give the Bakerian lecture, an unusual honour - which would also be granted in 1808. In 1807 he told of his discovery of a previously unknown element, potassium, which he had isolated by means of electrolysis. His starting point was caustic potash, an alkali then prepared from burned plants. This he placed in a tube, with a platinum wire sealed into its closed end and with the open end in a bath of mercury. The platinum and the mercury then constituted the electrodes, and the caustic potash the electrolyte. When connected to the battery, with the platinum as the negative and the mercury as the positive electrode, the mercury oxidised the expected reaction and a small quantity of some unknown substance

(which Davy called an 'alkaligen') formed itself round the platinum. An experiment based on the same principles produced an entirely new substance from soda. Both experiments were described in the Bakerian lecture. The key question was whether the resulting products should be called metals. Davy's own thoughts, as noted in his paper 'New Phenomena of Chemical Changes', are worth quoting:

*The bases of potash and soda agree with metals in opacity, lustre, malleability, conducting powers as to heat and electricity, and in their qualities of chemical combination.*

The problem was that both, as metals, were extremely light, with specific gravities way below that of water - a property shared by no other metal. Davy, pointing out that other known (but much heavier) pure metals varied greatly in weight, finally saw it as proper to call the new substances 'potassium' and 'sodium', names in a form only appropriate for metals.

In any case, both newly discovered elements were very highly reactive in comparison with any known metals (which explains in part why it was so hard to decompose them). Bring potassium or sodium in contact with any other substance, including particularly liquids and gases, and a reaction, often violent, is almost certain to occur. No wonder that they never occur in pure form in nature. Davy himself, describing the way sodium formed at the negative electrode, told how 'the globules often burnt at the moment of their formation, and sometimes violently exploded and separated into smaller globules, which flew with great velocity through the air in a state of vivid combustion, producing a beautiful effect of continued jets of fire'.

The discovery of potassium and sodium is a landmark in the history of science. Both are essential elements for all living organisms. In animals (including humans) electrically charged atoms, or ions, of both elements, play a key role as transmitters of impulses in the nervous system; the positive potassium ion is also essential to protein synthesis in plants. Sodium bonds with chlorine (which was named by Davy) to form salt, an extremely stable compound of two highly reactive and unstable elements. Salt, or  $\text{Na}^+\text{Cl}^-$ , is regarded as the prototype of the ionic bonds.

Davy, having started with potassium and sodium, continued with electrolysis to isolate calcium, barium, strontium and magnesium, although here his contemporary, the Swedish chemist, Jons Berzelius (1779-1848) - also a pioneer in the use and understanding of electricity - was ahead of him. Berzelius visited Davy in London, but, although they used much the same techniques, they can hardly be called collaborators, as is clear from Davy's own continental travels, which started in March 1813. Davy only grudgingly accepted the achievements of foreign scientists, however eminent.

Working with electrolysis led Davy, in 1810, to discover the electric arc, by connecting the terminals of a giant voltaic cell to charcoal electrodes.

The arc crossed the gap arising when the electrodes were separated. One who witnessed this phenomenon reported 'a most brilliant ascending arch of light, broad and conical in form in the middle. When any substance was introduced into this arch, it instantly became ignited; platina melted as readily in it as in the flame of a common candle; quartz, the sapphire, magnesia, lime, all entered into fusion... The light, which was so intense as to resemble that of the sun, produced a discharge through heated air of nearly three inches in length, and of a dazzling splendour'.

The electric arc, still essential to welding, is a continuous electric discharge across the space between two electrodes: to start with the gap must be small, but the heat generated by thermal ionisation creates a conducting medium, across the gap, allowing it to be made much wider. This facility is built into any arcing system, so that the arc, once created, bridges the widest possible gap that will sustain it. The arc generates not only heat but also light, whose properties are determined by the chemical composition of the electrodes, which are not necessarily carbon. (Until Thomas Edison's (1847-1941) invention of the incandescent light bulb in 1879, arcs provided the only possible electric lighting.)

Davy, after being knighted by the Prince Regent on 8 April 1812, married a rich widow, Jane Apreece, three days later. This did not prove to be a happy move, because Jane's haughty disposition and social pretensions endeared neither her nor her husband to the company they kept. She no doubt had much to complain of: even on their honeymoon, spent largely in Scotland, Davy brought with him a chest of apparatus, so that he could continue chemical research. Once married, he largely abandoned his work at the Royal Institution, and in October 1813 he set out for France on the first of his continental journeys.

Davy was accompanied not only by his wife but also by a young man, Michael Faraday (1791-1867), who had been taken on as his amanuensis in March 1813. Judged in the light of Faraday's later scientific achievements, the company was extraordinarily distinguished. It was not happy, however: Lady Davy treated Faraday like a menial servant, and he was delighted when she succumbed to seasickness on the cross-channel voyage. Although it is easy to see Faraday as Davy's great apprentice, he himself saw Davy as 'a model to teach him what he should avoid'. None the less the three stayed together, and once ashore they headed for Paris, where all three behaved like typical Brits abroad. Already on disembarking, Faraday had found, as they were searched by French officials, that 'he could hardly help laughing at the ridiculous nature of their precautions'.

In Paris they received, among many other distinguished scientists, Joseph Louis Gay-Lussac (1778-1850) and Andre Marie Ampere (1775-1836) - almost exact contemporaries of Davy. Davy, invited to hear Gay-Lussac lecture at the Ecole Polytechnique, noted the experiments carried out, which with the help of

diagrams explained a new substance discovered by the lecturer. Davy immediately rushed a paper to the Royal Society, identifying a new element and calling it 'iodine' (because of its affinities with chlorine). Gay-Lussac, whatever he thought of being pre-empted in this way, kept his cool: Davy accused him of picking his brains, but accepted that he stood 'at the head of living chemists in France'. Considering that the Institut elected Davy as a Corresponding Member on 13 December, this was - to quote a well-known figure from the twenty-first century - inappropriate.

This was not all. In front of a distinguished French audience, Davy demolished Lavoisier's theory about acids - according to which oxygen was always an essential component - by showing that chlorine could replace oxygen. Faraday was much less arrogant, leading one French scientist, J. B. Dumas, to remark at the end of the day 'we admired Davy, we loved Faraday' a view which many in England would share. As for Davy, Napoleon is reported to have remarked that he held all the members of the Institut in low esteem. Davy himself, on leaving Paris with his wife and Faraday, spent the first night at Fontainebleau, where he wrote a poem predicting the fall of Napoleon. Here, as so often, he was right: the battle of Waterloo was only eighteen months away.

In Italy, where the grand tour continued, Davy was somewhat happier. In Florence, using the giant burning-glass of the Grand Duke of Tuscany to focus the heat of the sun on a diamond, he produced pure carbon dioxide, so confirming that diamonds were a form of carbon. (Although Lavoisier had conducted the same experiment in 1772, Davy's result was still significant.) In Rome he experimented with iodine and chlorine and their compounds with oxygen. Finally, he visited Volta, the man who had made everything possible in the first place, in Milan. Volta was dressed in his finest, Davy in his scruffy travelling clothes - British to the end.

Davy returned to England on St. George's Day 1815, just two months before Waterloo. Following the defeat of Napoleon, as predicted in his poem, he wrote to the Prime Minister, Lord Liverpool, urging that the French be treated with severity in any subsequent peace treaty. This came from a man who but two years beforehand had had every honour bestowed upon him in Paris: talk about *'la perfide Albion'*. To his mother he wrote, 'We have had a very agreeable and instructive journey, and Lady Davy agrees with me in thinking that England is the only country to live in.'

In the last ten years of his life, Davy was president of the Royal Society. There, in spite of his feelings about the French, he did his best to make the Royal Society more like the Academic des Sciences, a self-governing institution with election restricted to men with some recognised scientific achievement. Davy accepted that other scientific institutions in France, notably the Ecole Polytechnique, were better than anything in Britain although by this time the British universities were beginning to reform themselves. Although, while Davy was president, a majority of the members of



the Council of the Royal Society had published a scientific paper, radical reform had to wait until after his death.

Davy died in February 1829, barely fifty years old. Even so many of his greatest achievements date back to the 1800s, before he achieved wealth and a position in society. That he was a man spoiled by success is only half the truth: his constant devotion to nature, poetry and the sport of fishing reveal a mystic rather than a materialist. As a scientist and a reformer of scientific institutions, he was almost always right - too much so to make him at all lovable. He may have been as great a man as Volta, Berzelius, Gay-Lussac and Faraday - to name only a few of his great scientific contemporaries -but in purely human terms they all had something he lacked.

### **Dalton's law for compounding chemicals**

John Dalton (1766-1844), to all appearances a classic wimp, is rightly regarded as one of the founders of modern chemistry. His background explains both aspects of his life. Dalton's parents were Quakers in west Cumberland and brought their son up in a part of England where the Society of Friends was exceptionally well represented. This was the result of the industrial revolution, focused on Manchester - the hub of north-west England - in which Quakers and other religious dissenters had played a prominent role.

The result, for Dalton, was that he grew up in an area where education was largely in the hands of the family of believers into which he was born and of which he would remain a member for his entire life. The dissenting ethos (which owed much to the Quakers) denned a world, centred on Manchester, in which Dalton would always feel at home. With this background it is not surprising that Dalton always earned his living as a teacher; his first appointment came when, at the age of twelve, he took over as teacher in the local school. When he was fifteen, he moved to Kendal (forty miles from his home) to become an assistant in a school generously endowed by Quakers.

The school had a good scientific library, containing not only books but also scientific apparatus including a telescope, a microscope and an air pump. More important to Dalton, at least in his own view, was the patronage of another Quaker, John Gough, the blind natural philosopher and friend of Wordsworth, who also lived in Kendal.

With Gough as tutor, Dalton's interests focused on science, particularly meteorology, and in 1787 he began to keep daily records - a practice he maintained until his death fifty-seven years later. This was the beginning of his interest in the gases to be found in the earth's atmosphere. Of the elemental gases, Cavendish had already discovered hydrogen, Priestley oxygen, and Lavoisier nitrogen. Even earlier, in 1754, 'fixed air' (which would prove to be a

compound of carbon and oxygen) had been identified as different from the ordinary air we breathe.

In 1785 the principal of the Kendal School retired, and Dalton, helped by his older brother, took over. This does not mean that Dalton was content as a schoolmaster - far from it. He observed that 'very few people of middling genius, or capacity for other business', become schoolmasters. Dalton's first attempts to find something better failed, but he did become known, even outside Kendal, from the public lectures on mechanics, optics, pneumatics and astronomy, given with the aid of his school's scientific apparatus. In 1792, after visiting London for the first time, Dalton was appointed as the first professor of mathematics and natural philosophy at the Manchester Academy, recently founded by prominent local dissenters. This appointment brought him to just the right place, at least at the end of the eighteenth century. For as Disraeli later observed, 'What Art was to the ancient world, Science is to the modern; the distinctive faculty. In the minds of men, the useful has succeeded to the beautiful... rightly understood, Manchester is as great a human exploit as Athens.'

In the event Dalton liked Manchester better than the Academy, where he resigned his position in 1800. Instead he opened his own Mathematical Academy, which was an immediate success. The fees paid, and the freedom to organise his own life, meant that he could pursue the serious business of chemistry much more effectively. He had already begun to publish, and his first paper, submitted to the Manchester Literary and Philosophical Society (to which he had been elected in 1794), proved to be surprisingly influential.

Dalton's chosen subject was colour-blindness, an affliction that he shared with his older brother (although it was not then known to be hereditary). His theory about its causes, argued in meticulous detail, later proved to be wrong - as was confirmed when his own eyes, on his instructions, were dissected after his death. None the less, the condition was long known as 'Daltonism', although Dalton himself would never write about it again.

Dalton's most important work began only after he left the Academy, when the Literary and Philosophical Society provided a home for his apparatus and experiments, to say nothing of an up-to-date library and a journal which would publish many of his most important results. What then did Dalton achieve in the remarkable opening years of the nineteenth century?

In the new century Dalton's work with mixed gases - a development of his interest in meteorology - was critical. Towards the end of the old century, his study of the evaporation of water in the atmosphere, presented in his first book, *Meteorological Observations and Essays*, had led him to the conclusion that no chemical reaction was involved. The book also contained, in somewhat inchoate form, the proposition that in a mixture of gases every gas acts as an independent entity - 'Dalton's law of partial pressures'.

The result is that such a mixture operates effectively as a reservoir for all the gases contained in it, so that chemical processes can always access the particular gases they require and discharge the substances they then produce. A simple experiment shows how to observe this process at work: light a candle and, after allowing it to burn for a minute, cover it with a large glass. Within a few seconds, the flame will be extinguished. The process of combustion, a chemical reaction dependent on oxygen, having consumed the entire quantity contained in the glass, can no longer continue: so long as it lasted, carbon dioxide, a product of the reaction, replaced the oxygen to mix with whatever other gases were present in the atmosphere. The process would in no way have affected the chemistry of these other gases (although it might have affected both their temperature and pressure).

This was only half the story. By Dalton's day it was beginning to be clear that gases could combine in a reaction to make compounds. In particular, nitrogen could combine in two different ways with oxygen, one producing nitric oxide and the other nitrous oxide - the laughing gas familiar from Davy's early experiments. It could also combine with hydrogen to produce ammonia. There were also two different ways carbon (although not a gas) could combine with oxygen, and two more with hydrogen. In these cases the solubility of the gases in water was the focal point of Dalton's experiments. And then, of course, water was itself a compound of hydrogen and oxygen - the only one known, until the discovery of hydrogen peroxide in 1815. (Astrophysicists have now discovered a third such compound, hydroxyl, in interstellar dust.) Dalton's experiments in the opening years of the nineteenth century confirmed that 'compounds were formed from the combination of constant amounts of their constituents'.

Taking the case of the two oxides of nitrogen, in which the quantity of nitrogen in one is twice that in the other, there is no question of a gradual transition from one to the other. There is no way of progressively 'adding' nitrogen to nitric oxide so as to transform it into nitrous oxide: these two compounds of nitrogen are formed by quite different reactions. In the general case of two elements *A* and *B* having known compounds  $A+B$  and  $A+2B$ , further compounds may well be possible not only in the forms  $A+3B$ ,  $A+4B$ , and so on, but also in such intermediate forms as  $2A+3B$ . Additional elements *C*, *D*, and so on, occur in more complex compounds. For most elements the list of possible compounds is quite short; the great exception in carbon, whose capacity to combine in long complex chains underlies the whole of organic chemistry and biochemistry.

Dalton's discovery led him to weigh the different portions of each element occurring in a compound. Since this procedure can be carried out with any quantity, the only constant results it can produce are the ratios of the weights of the different portions to each other. This was Dalton's system of equivalent weights.

Now Dalton was concerned with a process of transduction, by which he pursued equivalent weights conceptually to the point at which the smallest unit still retaining all the properties of the element occurs. This led to Dalton's theory of the atom, although the concept of such a small fundamental unit was already current among his contemporaries. The problem, when working with portions compounded in molecules built out of such atoms, was how to be certain about the proportions of the elements occurring at this fundamental level.

Dalton's treatment of water is exemplary. The relative weight of the portions of oxygen and hydrogen was 7 to 1. Dalton, assuming a one-to-one ratio at the atomic level, calculated a molecular weight for water, not having any means of knowing that the water molecule in fact contains two hydrogen atoms. His weighing was also inaccurate, since the relative weights in a water molecule are 8 to 1, so that with two hydrogen atoms, an oxygen atom must in fact weigh 16 times as much as a hydrogen atom. Dalton, knowing no better, commonly assumed the simplest possible combination - e.g. with one hydrogen atom - not only with water, but also with ammonia ( $\text{NH}_3$ ) and other compounds. The problem always defeated him, as he was to note in 1814:

*"After having the atomic principles in contemplation for ten years, I find myself still at a loss, occasionally, to discriminate between the combinations which contain two atoms of a given body from those which contain only one atom".*

Dalton was, however, on the right track. In the course of time his mistaken proportions could and would be corrected. In particular, his support for the so-called integral weights hypothesis was extremely hesitant. According to this hypothesis, stated by Dalton's contemporary, William Prout (1785-1850), in 1815, the atomic weights of all the elements are multiples of that of hydrogen. On the other hand, in 1827 rather late in the day Dalton did accept that 'the greatest desideratum at the present time is the exact relative weight of 100 cubic inches of the element hydrogen'. Dalton should also have paid more attention to the Swedish chemist, Berzelius, who recognised him as 'one of the most ingenious physicians of our age'. Berzelius, a much more accurate experimenter, obtained results which both extended and modified those of Dalton. In particular, Berzelius accepted the law stated by Gay-Lussac in 1808 that when gases combine chemically, there is always a simple numerical relationship between the volume of those consumed and that of those produced. This then opened the way to finding in 1814 the correct ratio, 2:1, of hydrogen to oxygen atoms in water, which, if known to Dalton, would have saved him much trouble.

On the other hand, both Berzelius and Dalton ignored the important hypothesis stated by the Italian chemist Amedeo Avogadro (1776-1856) that equal volumes of all gases contain equal numbers of molecules when at the same temperature and pressure. Quite simply, Avogadro, coming from Turin, was not well placed to make an impact on the world of science. Nearly a half

century later, his compatriot, Stanislao Cannizzaro (1826-1910), convinced the world of the truth and importance of Avogadro's hypothesis. By this time the Russian chemist Dimitry Mendeleev was well on the way to establishing the periodic table of the elements.

### Chemical notation

The modern world is now so conditioned to chemical notation that there is little concern as to what lies behind it, whether in terms of its meaning or of its historical origins. A headline such as 'CO<sub>2</sub> emissions threaten global warming' begs any number of questions about the true nature of CO<sub>2</sub>. The word emission suggests that it occurs as the result of some sort of chemical process, and the notation suggests that this involves combining one measure of carbon (C) with two of oxygen (O). This principle is also enshrined in the familiar name 'carbon dioxide'. But what are these measures? Familiar dimensions, such as mass and length, provide no more than the first step towards the right answer. This is intuitively obvious, given that carbon is a solid and oxygen is a gas. At least since Lavoisier's day it has been clear to chemists that everyday compounds, whether gaseous (e.g. CO<sub>2</sub>), liquid (e.g. water, H<sub>2</sub>O) or solid (e.g. common salt, NaCl), combine elements with quite different characteristics.

The problem, historically, is that the compounds came first, although, particularly in the case of gases, they are not always recognised as distinct substances. Returning to the headline, the picture evoked, of a factory chimney discharging industrial waste in the form of gas into the atmosphere, could also have been that of a scenario from before the year 1754, when 'fixed air' - today's CO<sub>2</sub> - was first identified as a substance different from ordinary air. Even in these early days Thomas Newcomen's steam engines were already polluting the atmosphere. One hallmark of the revolution in chemistry is the transition from a vocabulary that in 1750 was chaotic to one that in 1850 was completely systematic. In 1750, the chemical lexicon, based on local language, varied from one country to another, and was hardly consistent in any one of them; in 1850 it was based on universally accepted abstract symbols. On the one hand, the transition was simply the result of lexical reform, the subject matter of this section; on the other, it required Mendeleev's discovery and organisation of the periodic table of elements, explained later in this book.

The movement for lexical reform started in the Academie des Sciences, and, although it was originally confined to French, the principles governing it could be, and in due course were, applied to other languages - notably English. Lavoisier, who led the reform, set the ball rolling with a paper entitled 'The Need to Reform and Improve Chemical Nomenclature', presented to the Academy in 1787. Lavoisier was not an entirely disinterested reformer: he intended

to restate chemistry in terms which implicitly accepted the correctness of his new theories. His textbook, *Elements de chimie*, published in 1789, was largely written to confirm this position. The question is, what did Lavoisier have to work with? And how did he then devise a suitable lexicon?

The basic material available was simply state-of-the-art chemistry, as Lavoisier regarded it in the mid-1780s - incorporating, therefore, even those parts of his own work still open (rightly as we now know) to dispute.

Lavoisier's list of simple substances was divided into four parts. Part 1 contained 'simple substances belonging to all the kingdoms of nature, which may be considered as the elements of bodies'. The status of oxygen, azote (nitrogen) and hydrogen, the three elemental gases known to Lavoisier, is still unquestioned, although time would add another seven to this category - one, chlorine, within a generation. Light was included because Lavoisier saw it as the fundamental principle of vegetable chemistry (observed as photosynthesis), and caloric as the basis of heat and expansion.

By Lavoisier's day, sulphur and phosphorus were well established as non-metallic elements, which is the defining property of part 2. Charcoal, as representative of carbon, is in the same class. The three radicals had not been correctly identified. In the 1770s, the muriatic and fluoric radicals, derived from chlorine and fluorine, were discovered by the Swedish chemist, Carl Scheele (1742-86), who passed on his experimental results to Lavoisier. In 1808 the boracic radical would lead to the independent discovery in both France and England of the element boron (never found free in nature).

Part 3 contained seventeen metals, of which six, bismuth, cobalt, manganese, molybdenum, nickel and tungsten, were discovered in the middle years of the eighteenth century (three by Scheele), while the rest had been known much longer, most since antiquity. Lavoisier's comprehensive description, 'oxydable and acidifiable simple metallic bodies', derived from his own experiments, attributed properties hardly relevant to metals, such as gold and platinum, low on the scale of reactivity.

Part 4 - 'salifiable simple earthy substances' according to Lavoisier's heading contained five substances commonly occurring in nature, known since antiquity and useful for any number of practical purposes. Although they are all compounds, a particular element, not isolated in Lavoisier's day, characterises each one. These elements, calcium, magnesium, barium, aluminium and silicon, would all be isolated within a generation of Lavoisier's death.

Taking a synoptic view of the four categories, twenty-three of the substances listed are actual elements, while eight foreshadow elements on the threshold of discovery when Lavoisier died. Surprisingly, perhaps, Lavoisier failed to include potash and soda, the source of the first two elements, potassium and sodium, to be isolated by Davy. Leaving aside light and caloric, Lavoisier's table provided a remarkably solid basis for developing chemical nomenclature and notation.

Lavoisier's work was carried on by two younger contemporaries, Claude Berthollet (1749-1822), who had collaborated with him, and the Swedish chemist Jons Berzelius (1779-1848). Berthollet's realisation of the essential connection between the way a reaction takes place and the mass of the reagents opened the way to chemical formulae as we now know them. Berzelius, who himself discovered three elements (including silicon), lived to see the elemental base of all the substances in Lavoisier's table established; although he never reached seventy, of the fifty-four elements known when he died, thirty had been discovered during his lifetime.

Berzelius, a year younger than Davy, is regarded by many as his equal, but his real focus (shared in correspondence with Davy) was on the work of John Dalton. Like Davy he achieved distinction early in life, becoming, at the age of twenty-eight, professor of medicine in Stockholm, but sadly - again like Davy - his last years were troubled by professional discord. Unfortunately he never found a good biographer, and although he corresponded in English and French, his annotated letters are to be found only in a Swedish edition. The record, therefore, consists largely of his published scientific work. This reflects 'his massive contribution... unique in the history of chemistry. His systematic mind saw the need for a structure in which chemistry could grow with the precision and the articulation of a living organism. The basic principle of his design was atomic composition.'

Berzelius's new chemical symbolism was intended to replace that developed by Dalton. Where Dalton used circular signs, Berzelius used letters. Although he was not the first to do so, his system, as it developed in the course of some twenty years, proved superior to any its rivals and is still that in use today (so that expressions like  $\text{CO}_2$  even appear in tabloid headlines). These were 'destined solely to facilitate the expression of chemical proportions', but they were also much easier to write or print.

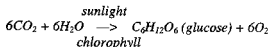
### **Photosynthesis and the life of plants**

If the phenomenon of light, generally regarded, belongs to physics, it still governs a number of important processes in chemistry. The best known is that of photosynthesis, in which the light of the sun is essential to the growth of green vegetation, which in turn stores the energy absorbed from the sun. The actual process, or rather its results, was observed by the earliest representatives of humankind: it was, after all, essential for the food chain. An understanding of the process had to wait, however, until the end of the eighteenth century.

The first breakthrough came in 1771, when Joseph Priestley noted that green plants emitted oxygen. Eight years later, in 1779, Jan Ingenhousz (1730-99) (a Dutchman who had come to live in England), established that

sunlight was essential to their growth, and in the same year the Swiss Jean Senebier (1742-1809) published in his *Action de la lumiere sur la vegetation*, the general principle: this is that a plant, by absorbing carbon dioxide (CO<sub>2</sub>) from the atmosphere, and water (H<sub>2</sub>O) from the ground, produces glucose (the basis of all carbohydrates), at the same time releasing oxygen (O<sub>2</sub>).

Chlorophyll, a green compound to be found in the leaves of plants, is essential to the process, which can be stated formally as follows:



The importance of the process is that it produces an astonishingly wide range of organic compounds essentially the whole of plant life - which by chemical reaction can release energy. In living species this is the process of metabolism by which life is maintained. Equally plants can be used as fuel for combustion, either in the form of their natural growth or after being subjected in a decadent form to external forces (mostly geophysical) over long periods of time. Typically the former process produces wood, and the latter, coal and oil - the so-called fossil fuels. It was one of Lavoisier's great insights to see that the two processes were essentially the same. Since early times both have been extended by human invention, from cooking vegetable matter to burning charcoal - to say nothing of modern industries such as oil refining.

### **Photography: the inorganic chemistry of light**

According to a phenomenon already observed in the sixteenth century, certain naturally occurring silver salts become dark on exposure to light. In the first half of the nineteenth century it was discovered that these salts were those of chlorine, bromine and iodine - all elements discovered in the period 1810-26. Louis Daguerre (1789-1851) in France and William Henry Fox Talbot (1800-77) in England, acting independently, used their understanding of the basic phenomenon to invent photography - that is, a chemical process by which a fleeting image could be recorded in permanent form.

The process itself belongs to technology rather than science. Myriads of minute silver salt crystals are uniformly distributed over a flat surface covered by an emulsion. An image focused on the surface then causes each separate crystal to darken in proportion to the light incident upon it. The result is a photographic negative: the bright parts of the image became dark, and the dark parts, bright. The problem, still familiar to amateur photographers, is to stop the process and fix the image when it has reached the most satisfactory stage of development.



The solution came by realising that, on exposure to light, the ions composing the salt (e.g. positive silver and negative chlorine) separate and, by electron transfer, transform to the basic elements, a process completed by a developing solution. The untransformed salt crystals (i.e. those not exposed to light) can then be eliminated, leaving only a residue of black metallic silver constituting the photographic negative. If the surface containing the emulsion is transparent, the process can be repeated with emulsified paper, reversing the colours so as to produce a positive image.

Basically this is all photography adds up to, at least before the recent invention of the digital camera (although the colour photography developed by Gabriel Lippmann (1845-1921) and Lord Rayleigh (1842-1919) should perhaps be noted). In the early days the usefulness of photography to science was limited by poor resolution and long exposure times, but better optical systems and creative chemistry in the emulsions (which continued to be based on silver) cured these defects to the point that from about 1850 onwards photography became an essential adjunct to astronomy (particularly after Lippmann's coelostat enabled a telescope to follow the movement of the stars). The first ever photographs of a solar eclipse, taken in 1851, represent a key breakthrough. Following astronomy, almost all optical instruments made use of photography in one way or another, and as we shall see later in this chapter this use extended beyond light waves to other forms of radiation such as X-rays. This is particularly true of spectroscopy.

### **Spectroscopy: the rediscovery of light**

In optics, until the end of the eighteenth century, there was little advance on Newton's discovery that a prism resolved the light of the sun into the series of colours that make up the spectrum. In the middle of the century, a young Scotsman, Thomas Melville (1726-53), had noted the presence of a brilliant yellow light in the flame of burning alcohol, when other substances, notably salt, were added. This, the distinctive line of sodium, then aroused little interest, perhaps because Melville, dying at the age of twenty-seven, had too little time to establish a scientific reputation.

This was not the case with William Wollaston (1766-1828), a wealthy man born into a family of scientists, who in 1802 observed seven dark lines in Newton's spectrum when this was obtained from a beam of light passed through a narrow slit only one-twentieth of an inch wide. This was just the beginning. In the years 1814-17, Joseph von Fraunhofer (1787-1826), a Bavarian master glass-maker, following up Wollaston and using his own improved lenses, developed the prism spectrometer. This, an optical instrument of unprecedented precision, made possible a whole new science of spec-

troscopy, which, as it developed and expanded in the following two centuries, would transform the universe of science.

Fraunhofer, using a telescope to observe spectra, saw not only Wollaston's seven dark lines, but hundreds of others. He counted 600, which he recorded on a map, in which the most prominent were given the letters A, B, C,... starting at the red end of the spectrum - the system still used today. This was a remarkable discovery, but Fraunhofer, an instrument-maker rather than a scientist, could never explain its significance - perhaps because he also died too young. The breakthrough came with two other German scientists, Robert Bunsen (1811-99) and Gustav Kirchhoff (1824-87) - two of the best-known names in nineteenth-century science. Although in early nineteenth-century Germany culture and language were more or less uniform, there was no German state. Instead, the common culture area was ruled by a great number of princes, whose courts largely determined not only the character of law, politics and administration but also the support given to science. Matters of state reflected a general concern for the impact abroad of the French Revolution, which had led to the fall of Europe's most powerful kingdom - not a happy augury for German princes - and introduced any number of unsettling new principles into politics, religion and education. The result in Germany was that both radical and reactionary ideas flourished, subject at local level to the politics of the court, which were generally conservative.

This climate favoured science. More than any other Germans, scientists were cosmopolitan, and at home, not only where German was spoken, but in France, England and even, occasionally, Sweden and Russia. France, throughout the revolutionary period, continued to lead in scientific discovery, and many a German prince, anxious not to be left behind, patronised and encouraged science (hoping at the same time to avoid the dangerous ideas that could accompany it). This was a great gain to both the universities and the scientists who taught there. The princes were not disinterested sponsors: the King of Bavaria, when he appointed the American Count Rumford to introduce the potato and supervise the royal arsenal, set a precedent for combining science with practical politics and economic policy. In the nineteenth century, the German princes were keenly aware of the practical advantages of sponsoring science.

Such was the background to the life and work of Bunsen and Kirchhoff. Both came from comfortable families of academics and court officials, established in old university towns - Göttingen in the Kingdom of Hanover in the case of Bunsen, and Königsberg in the Kingdom of Prussia in the case of Kirchhoff. In middle life their paths would cross, first in Breslau (in Saxony) and then in Heidelberg (in Hesse), where, as close friends, they collaborated over a long period. Both would live to see the unification of Germany, in 1870, orchestrated by Prince Bismarck, the Iron Chancellor of Prussia.

Bunsen, although a sometimes impetuous schoolboy (who once overturned his desk when the master made a joke at his expense) achieved, aged seventeen, a distinguished *abitur* - or high-school diploma - and went to follow a broad science syllabus at his home university. He shone as a student, but he also learnt glass-blowing (useful for a chemist) and made a chemical balance good for weights from 10 milligrams to 200 grams - a remarkable range. This also came in useful in a life of scientific experiment.

In 1830 Gottingen became a centre of radicalism at the time of the French July revolution, with professors refusing the loyal oath to the King of Hanover. Bunsen, already busy with his doctoral thesis, maintained a low profile, and his prudence was rewarded by a government travelling scholarship. This led to two years of travel, in which Bunsen visited almost every continental centre of scientific research. He spent the longest time, eight months, in Paris, and then, in 1833, in St. Etienne, much further south, he saw a railway for the first time, and travelled by train - predicting, correctly, that trains would also come to Germany (as they did two years later). Ironically, Austria, because of the revolutionary events in Hanover, first denied him entry, but he still made it, finally, to Innsbruck and Vienna. (In contrast to the German princes, the Habsburg emperors were seldom patrons of science.)

Once home, he completed his doctorate with distinction, and while busy working to qualify as *Privatdozent* in chemistry, accepted, in 1836, a well-paid job in Kassel (in Hesse) with plenty of time for his own research. He was still, apparently, impetuous: he was first nearly blinded by a laboratory explosion, and then, while researching the chemistry of poisons, spent several days near death after experimenting with potassium cyanide. The chapter of accidents continued throughout his life, and when he was fifty-seven only his left hand, held before his eyes, prevented his being blinded by another explosion. Finally, when he was already sixty, all his papers, photographs and drawings were lost in a fire. Undiscouraged, he built up his collection again before the publication, in 1875, of his comprehensive *Spektralanalytische Untersuchungen*.

From the beginning, Bunsen's exceptional talents were recognised. Although his work at Kassel was important economically for Hesse, Bunsen, never out for gain (unlike many distinguished contemporary scientists - Liebig, Mond, Siemens - among his compatriots), was noted for saying 'work is fine, acquisition, contemptible'. Aged twenty-eight, his talents brought him a professorship at Marburg where he invented a cheap and efficient zinc-carbon battery, which he then used to produce electric arcs between metal electrodes: during his evening lectures he beamed the brilliant light of the arcs on the neighbouring Elizabethkirche.

Reactionary politics in Hesse, following the revolutions that swept Europe in 1848, led Bunsen to move to Breslau (in Saxony) in 1851. He stayed only a year, moving on to Heidelberg in 1852, attracted by a high sal-

ary and the promise of a new laboratory - so foreshadowing the familiar career structure of twentieth-century academia.

In Breslau, Bunsen, with the help of his zinc-carbon battery, was the first to use electrolysis to produce magnesium on a large scale, and in Heidelberg he added chromium and aluminium. There, also, with the gas supply in his new laboratory, Bunsen adapted a gas-burner brought from England by Henry Roscoe, so as to produce a burner in which the gas-air mixture could be controlled to produce different sorts of flame. This became the world-famous Bunsen burner, part of the essential equipment of any laboratory (and also the basis of today's gas cookers). For Bunsen himself, it made possible experiments in spectroscopy, by which he, together with his friend Gustav Kirchhoff, would transform both physics and chemistry.

Bunsen met Kirchhoff for the first time in Breslau and in 1854 arranged his appointment to a chair in Heidelberg. So began a most fruitful and amicable collaboration between two men of exceptional ability. Kirchhoff, although no less gifted than Bunsen, differed from him in both manner and appearance. Bunsen was a self-confident extrovert, with a massive and somewhat rough-hewn physique, unconcerned about the risks his experiments involved. Kirchhoff, diffident and uncertain, a theorist rather than an experimentalist, was small and somewhat effeminate - the perfect foil to Bunsen. It was said later that 'Bunsen's greatest discovery was Kirchhoff'.

As a schoolboy and student Kirchhoff shone as brightly as Bunsen. At the age of twenty-two, he published his doctoral thesis, which contained the first version of the fundamental laws governing electric currents and conducting systems - now known simply as Kirchhoff's laws. This success led the Physikalische Gesellschaft in Berlin (the capital of Prussia) to offer a grant for a year's study in Paris. Kirchhoff never made it, frightened by the revolutionary political situation in France. Instead he spent the time in Berlin, where he continued to build his reputation to the point that in 1850 at the age of twenty-six he could accept the chair of experimental physics in Breslau.

Sadly, as so easily happens in academic life, he clashed with another professor in the department, took sick leave on doctor's advice, and went back home to Königsberg. There he met Hermann von Helmholtz (1821-94), recently famous for his work on the conservation of energy, who immediately befriended and admired him. But at Breslau Kirchhoff had met Bunsen, who together with Helmholtz orchestrated his appointment to Heidelberg in 1854. (Bunsen had wisely advised Kirchhoff, a colossal self-doubter, not to give way to untimely modesty in making his formal application.)

At Heidelberg, Kirchhoff equalled Bunsen as a lecturer (with two of his students, Gabriel Lippmann (1845-1921) and Heike Kamerlingh-Onnes (1853-1926), later becoming Nobel prizewinners). Kirchhoff also showed that electric currents in narrow wires propagate as waves with the speed of light, a key result in the later experimental work with radio waves of another

of his students, Heinrich Hertz (1857-94). Bunsen and Kirchhoff, almost inseparable, were familiar in the streets of Heidelberg, in deep scientific conversation as they walked together. (In proportion they must have resembled Helmut Kohl and Francois Mitterand). On one of the walks, a sunset seen from the wooded heights above Heidelberg led them to look at spectral analysis. Although others were already active in this field, Bunsen and Kirchhoff, by consolidating and extending their results, established spectroscopy at the heart of both physics and chemistry.

After Fraunhofer's discovery of dark spectral lines in sunlight, the next key finding was that other light sources, besides the sun, had distinctive lines. The Norwegian Anders Angstrom (1814-74) discovered that a spark between two metal electrodes contained the spectral lines of both the metal and the gas medium, which, in contrast to those of sunlight, were light rather than dark. Further advance was then blocked by failure to understand a distinctive yellow line occurring in almost all spectra. In 1857, William Swan (1818-94) showed that this was always a sign of a sodium compound, present even when common salt was but one part in 2,500,000 of the substance producing the spectrum. Bunsen and Kirchhoff then showed that it corresponded to Fraunhofer's D-line, and, given the ubiquitous traces of salt in the atmosphere - the result of oceans covering two thirds of the earth's surface - the practical problem was how to eliminate it from the laboratory.

One problem remained unsolved: why were the lines of the sun's spectrum dark, whereas those of spectra produced in the laboratory were light? According to Kirchhoff, 'this was either a nonsense or something very important'. In 1859 he examined the sun's spectrum through a yellow sodium flame, to find that instead of masking the dark sodium line (as he had expected) it accentuated it. He then obtained the same result in the laboratory by substituting an intense white incandescent light for the sun. Kirchhoff's explanation (which proved to be correct) was that light of a given wavelength would absorb incident light of the same wavelength, in a phenomenon comparable to resonance. For this reason the dark lines became known as absorption lines (in contrast to the bright emission lines).

This is the fundamental principle that for 'rays of the same wavelength at the same temperature the relation between the emission and absorption power is the same with all bodies'. This led to Kirchhoff's concept of black bodies absorbing all light incident upon them - later to become a key factor in heat-radiation research.

This also explained the Fraunhofer lines: the sun's spectrum, with its dark lines, is nothing other than the inverse of the spectrum produced by the sun's atmosphere. Spectral analysis of the sun's atmosphere could then proceed by taking the dark lines to correspond to the bright lines produced by any substance when heated in a flame. This culminated, in 1860, in the publication of Kirchhoff's *Chemische Analyse durch Spektralbeobachtungen*, based largely on experiments carried out by Bunsen.

In spectroscopy the practical problem was to produce, first, in purest possible form, different salts for each metal, and then, by use of electric arcs or different flames, to make them incandescent - for otherwise there would be no light to analyse. It was essential that the character of different flames, with their vast differences in temperature, would not affect the exact location of the separate spectral lines of the metals investigated. Bunsen and Kirchhoff showed how bright lines, according to their location in the spectrum, indicated the presence of particular metals. This was an extremely accurate analytical tool, especially for small quantities, although some results were foreshadowed by work done by others.

One experiment detected sodium vapour diluted to one part in 20,000,000, and although no other metal had such a prominent spectrum, very small quantities of lithium, strontium, calcium, potassium and barium could be observed in the same way (an economically significant result when it came to prospecting for metals whose sources were widely dispersed).

Bunsen and Kirchhoff also used spectroscopy to detect new elements. In particular, they expected the discovery of a fourth alkali metal next to potassium, sodium and lithium - showing only two lines in their spectroscope. They described the characteristic lines of the then undiscovered caesium in the blue part of the spectrum, and went on to do the same for rubidium with its characteristic dark red lines. Finding actual specimens of these two elements was very difficult: 44,200 kilograms of salt solution had to be processed to produce 7.272 grams of caesium chloride and 9.237 grams of rubidium chloride.

Finally, the correspondence between absorption lines observed in sunlight and iron emission lines observed in the laboratory was so exact that it could not be the result of chance. The only possible explanation was that iron was present in the sun's atmosphere. This line of reasoning led to the further discovery on the sun of thirteen known metallic elements, together with hydrogen.

Kirchhoff's absorption research also showed that the sun has a very hot light core, covered by a cooler layer containing the vapour of the elements discovered spectroscopically. Similar methods could be applied to analyse the composition of stars, which, earlier in the century, the French philosopher Auguste Comte had cited as an example of things that were inherently unknowable. In historical perspective, Bunsen's and Kirchhoff's disproof of Comte's claim introduced the new science of astrophysics.

The pioneering work of Bunsen and Kirchhoff was soon followed by others, using high-quality custom-built apparatus. First came William Crookes (1832-1919), who in 1861 discovered thallium after noting a bright green line in the spectrum; two years later indium was discovered in Germany; and at the end of the day, spectroscopy was to play a part in the discovery of twenty-one out of the twenty-seven elements discovered between 1860 and 1910.

(Some of these, notably helium, were first discovered on the sun before being found on earth.)

Bunsen and Kirchhoff were never able to discover the theory underlying the exact location (in terms of wavelength) of the distinctive spectral lines characteristic of any element: this, when it came, belonged to physics rather than chemistry and was one of the fundamental achievements of the great Danish physicist Niels Bohr (1885-1962). By this time, spectral analysis had extended far beyond the outer limits of the visible spectrum, although as early as 1800 William Herschel (1738-1822) had found that the heat spectrum extended into the infrared, while a year later Johann Ritter (1776-1810) showed that the darkening of silver halides (as in photography) continued into the ultraviolet. In this way three spectral zones were established, but the full implications only began to become clear at the end of the nineteenth century.

### The noble elements

Then, in 1893, Sir William Ramsay (1852-1916) looked at the question put by Lord Rayleigh (1842-1919) as to why nitrogen separated from air always proves to have an atomic weight higher than that of nitrogen produced in the laboratory. To find an answer, Ramsay separated both the oxygen and nitrogen from a sample of air using established laboratory methods. He found a residue, which could only be some other gas, equal to about 1% of the original volume. This was argon, and two years later, Ramsay isolated another similar gas by boiling a mineral called cleveite, which spectral analysis proved to be helium, first discovered nearly thirty years previously in the sun's atmosphere.

On the basis of atomic weight, argon had a place between chlorine and potassium in the periodic table, while helium should fall between hydrogen and lithium - the two elements with lowest recorded atomic weights. The need to accommodate these new elements could be met by introducing a new column - column 8 - but helium and argon would then occupy only two of the six places in it, at the end of rows 1 and 3, leaving rows 2, 4, 5 and 6 still to be filled.

Ramsay was plainly on a winning streak. In 1898, working with liquefied air (which technology had only recently made available) he once again eliminated the oxygen and nitrogen, and examined the residue spectroscopically. In this way the distinctive lines of three previously unknown elements, neon, krypton and xenon, appeared. The gaps at the end of rows 2, 4 and 5 were filled. Finally, in 1907, Ramsay showed that radon, discovered in 1900, should be placed at the end of row 6: column 8 of Mendeleev's table was therefore complete in the year of his death.

How could it be that not one but six elements had escaped the notice of chemists until the end of the nineteenth century, when the great rush to find 'new' elements, led notably by Davy, had started at its beginning? Chemistry was transformed in this century, which closed appropriately with the discovery of the 'new' elements in column 8. But why were they not discovered earlier?

The answer to this question is to be found in the basic phenomenon of all chemistry, the reaction between different substances, whether elements or compounds. Strong, sometimes violent, reactions are characteristic of the elements in columns 1 and 7 - just think of all those laboratory explosions. The reactions are often such that extremely unstable elements combine to form the most stable compounds: here common salt, a so-called ionic compound ( $\text{Na}^+\text{Cl}^-$ ) of sodium (column 1) and chlorine (column 7) is exemplary. The column to which an element belongs defines its reactive potential, but what if an element will not react with any other? In the first place, there is then no chemical phenomenon, whether occurring in nature or the laboratory, that will betray its existence. No-one can smell or taste it, or, if is a gas, feel it, and it will have no power to corrode, contaminate, or even decay, for all these everyday processes depend on chemical reactions. No wonder argon was given that name, which means 'lazy' in Greek. Argon was discovered only when it occurred to Ramsay to use chemical reactions to separate the other gases, oxygen and nitrogen, occurring in air. He could not touch argon in this way, and it was only towards the end of the year 2000 that the first chemical compound, ever, was produced from argon.

Appropriately the six elements in column 8 are known as the inert gases: this is just what they are. They are also known as the noble elements, because of their disdain to combine with the lesser elements in columns 1 to 7. They could only be detected when, in incandescent state, they produced distinctive spectra: for all except helium this state was created artificially in the laboratory. Helium was observed first in the sun's atmosphere, where its incandescence is the result not of a chemical but of a nuclear reaction.

Mendeleev first compiled the periodic table in 1869. With the emergence of nuclear physics in the twentieth century, with its capacity to produce new elements with atomic weights approaching 300, it is difficult to state a precise number for those discovered since that year - somewhere around forty is the best possible estimate. No matter: whatever the number, twenty-one had been forecast by Mendeleev. This is but one measure of the achievement of one of the most remarkable men in the history of science.



## Organic chemistry

For more than a hundred years, in the popular understanding of science, no distinction has been more clear-cut than that between organic and inorganic chemistry. Two hundred years ago, when the achievements of Lavoisier, Dalton, Priestley, and many others were beginning to make chemistry a hard science and give it its modern form, this particular distinction would have been meaningless. At the beginning of the nineteenth century, organic chemistry, according to one of the pioneers in the field, Friedrich Wohler (1800-82), was 'like a dark forest with few or no pathways'. In 1828 he showed that urea extracted from a dog's urine was identical to ammonium cyanate produced in the laboratory - a major step in bringing light into the dark forest. This was a sensational discovery, since it showed that no special 'vital' principle governed chemical processes taking place within a living organism. The end of *vitalism* can be said to open the way to biochemistry, although its potential for development was little realised at the time.

It was not so much Wohler as his friend and colleague Justus von Liebig (1803-74), who 'revealed the source of richness... of organic chemistry, that the simple elements of Carbon, Oxygen, Hydrogen and Nitrogen could combine together in myriads of different ways to produce millions of different compounds'.

During his youth, Liebig could witness, at first hand, the state of the art in proto-industrial chemistry. His father, who sold paints and other household wares in a *drogerie* in Darmstadt - the capital city of a German Grand-Duchy - produced much of his stock-in-trade in his own workshop. With eight children, the family was far from prosperous, and Liebig had to spend much of his time helping in his father's business. In his spare time, however, Liebig was able to study books on chemistry in the library of the Grand-Duke Ludwig of Hesse-Darmstadt. By good fortune Karl Wilhelm Kastner (1783-1857), a professor of chemistry, was one of his father's clients. Although in later life Liebig was derisive about Kastner's competence as a chemist, the professor still took him on as an assistant and then recommended him to the Grand-Duke.

With noble patronage Liebig was able to spend some months in Paris, working with Gay-Lussac, one of the greatest scientists of the day. There he also met the great German naturalist, Alexander von Humboldt, who recommended him to the Grand-Duke for an academic appointment. This led Liebig to the University of Giessen in 1824, and in 1825 he became effectively head of a new department of chemistry with a well-endowed laboratory. There he focused his research on organic chemistry and built up one of the best teaching and research schools in Germany. The University of Giessen is now named after him. Talk about success.

The great Swedish chemist Berzelius, a generation older than Liebig, had always seen 'the discovery of the rational constitution' as the main problem in organic chemistry, insisting at the same time that 'organic bodies obey the same general laws as... inorganic combinations'. The key was to be found in the idea of the radical, which since the time of Lavoisier was defined as the 'stable part of a substance that retains its identity through a series of reactions even though it was known to be a compound'. (This recalls the 'molecule integrante' proposed by Haüy for the analysis of crystals.)

By 1830 not only Berzelius and Liebig, but also Bunsen at Gottingen, were all sold on radicals. The problem was that for too many well-known substances different radicals could be found, and the choice of different radicals could lead to conflicting results. There were endless disagreements about how molecules combined, partly because of confusion about atomic, equivalent and molecular weights. (This was a generation before Mendeleev sorted out such matters.) By the mid-1830s the term radical came to indicate a hydrocarbon group or chain, so that the fundamental nucleus becomes an unsaturated hydrocarbon,  $C_8H_{12}$ . (Strictly a hydrocarbon is any chemical compound containing only hydrogen and carbon, but the number of such compounds is very great.)

In the mid-1840s some order was brought by the 'homologous' series introduced by the French chemist Charles Gerhardt (1816-56), who had earlier studied with Liebig. This is the so-called 'ladder of combustion': the formula  $C_nH_{2n}O_2$  for primary alcohols, is an example, with each successive value of  $n$  denning one member of this class.

In 1847, a young man with the unlikely name of Friedrich August Kekule von Stradonitz, having come to Giessen to study architecture, fell under the spell of Liebig, who advised him to study chemistry in Paris. Once there he became a friend of Gerhardt. As chemists, though not as friends, the two were soon to part company. Kekule forsook Gerhardt's principle based on one key type of atom for one in which 'no atom was more important than another in a constitutional formula'. Kekule's method of classification depended on how many other atoms or groups a given atom combined with, so that, for example, carbon is classed as 4, both oxygen and sulphur as 2. In 1859 Kekule introduced the principle of catenation, according to which carbon atoms were linked in a chain.

According to some sources the idea came to Kekule in the summer of 1854, when he fell asleep on the top of a London omnibus; but, however that may be,

*In the cases of substances which contain several atoms of carbon, it must be assumed that at least some of the atoms are in the same way held in the compound by the affinity of carbon, and that the carbon atoms attach themselves to one another, whereby a part of the affinity of the one is naturally engaged with an equal part of the affinity of the other... For example a group of*

two carbon atoms,  $C_2 \dots$  will form a compound of six atoms of monatomic elements, or generally with so many atoms that the sum of the chemical units of these is equal to six.

An elementary example of this is carbon and hydrogen combining to form ethane ( $C_2H_6$ ). The rule stated by Kekule is fundamental, and led finally to his defining organic chemistry as 'the chemistry of carbon compounds'. At the same time it was also applied to the general principle of valency (developed by Edward Frankland (1825-99) in England) which governs all structural chemistry, by stating precise numerical rules according to which atoms bind together to form molecules. This led to the familiar glyptic or 'croquet ball' models of molecules. The standard three-dimensional version shows a molecule of phosphorus pentoxide ( $P_4O_{10}$ ) and to be found in any introductory textbook, was only introduced by the Dutch chemist Jacobus van't Hoff (1852-1911) in 1874.

Van't Hoff also proposed that the four carbon bonds are directed to the corners of a tetrahedron, which then determines the arrangement of the atoms in the molecule of any carbon compound. More generally, according to the Russian physicist Alexandr Butlerov (1828-86), who had popularised the phrase 'chemical structure',

*Only one rational formula is possible for each compound, and when the general laws governing the dependence of chemical properties on chemical structure have been derived, this formula will express all of these properties.*

This was an oversimplification, and by the 1920s it was becoming clear that the question of structure was extremely problematical.

Kekule is best known for his discovery of the benzene ring - at least in the world of chemistry. Outside, Kekule's renown is more problematic, if only because the problem of benzene is not very transparent. Benzene was first identified, in compressed oil gas, by Faraday in 1825 (when he was still working as a chemist under the shadow of Davy). This result was published (although the name 'benzene' was coined by Eilhard Mitscherlich at Berlin in 1834). In 1850, the German chemist, August von Hoffman (1818-92) showed that benzene belonged to the chemical family of aromatics, of which it is now the prototype.

The problem was how to reconcile its chemical formula,  $C_6H_6$ , into the bonding principles established by Kekule for the carbon atom. Once again, tradition has it that the solution came to Kekule in a dream, this time after he had fallen asleep by his fireside. The answer was to form a ring of six carbon atoms, each of which was bonded to a hydrogen atom. After he had dreamt of this solution, Kekule asked, 'What else could a chemist have done with two valencies left over?' Kekule thought he had discovered 'an inexhaustible treasure trove', and at a memorial lecture in London, two years after his death in 1896, it was stated that Kekule's benzene

theory was the most brilliant piece of scientific production to be found in the whole of organic chemistry... three-fourths of modern organic chemistry is, directly or indirectly, the product of his theory.

Organic chemistry, as practised in the nineteenth century, took little account of the fact that the whole chemistry of plant and animal life (in geological time the source of many organic compounds, such as all fossil fuels) was also based on molecules containing carbon atoms. This is the realm of biochemistry, a science that did not develop significantly before the twentieth century, although some phenomena, such as photosynthesis, had been examined much earlier. In the second half of the twentieth century, molecular biology led to any number of remarkable discoveries, and with the complete decoding of the human genome, these are set to continue in the present century. This defines a science quite beyond anything that Kekule, the great dreamer of nineteenth-century chemistry, ever conceived of. It is also beyond the scope of this book.

### **The magic of crystals**

Crystals, one of the most common forms taken by solid matter, have played a part in human culture since prehistoric times, with magical powers often being ascribed to them. Their appearance, although far from uniform, always discloses something of their distinctive properties. These are remarkably wide ranging, and relate to optics, electricity, chemistry, geology and even the life sciences. Crystals' close relationship to minerals, the basic substance of rocks, defines such characteristic properties as hardness, lustre, colour, cleavage and fracture. The problem is the sheer diversity of crystalline minerals, so that classification has always been an important part of crystallography. Some crystals, such as quartz, are extremely common. Even so, this, the most abundant of all minerals in the earth's surface, occurs not only as common rock crystal but also as amethyst, chalcedony, agate and jasper. It is no wonder then that it has always attracted humankind, and continues to do so in its modern applications in timepieces, electronics, optical instruments and abrasives - to say nothing of jewellery.

In the written record of science, going back to antiquity, crystals are seen to have interested any number of great men. Democritus, Plato and Aristotle - each with his own theories on this subject - head the list, but it goes on to include Newton, Hooke, Boyle, Huygens, van Leeuwenhoek, Lavoisier, Linnaeus, and many others: the list could continue indefinitely. There are also the lesser-known actors such as, notably, the Abbe Rene Just Haüy (1743-1822), who gave Linnaeus the honour of being the father of crystallography, a title he could well have claimed for himself.

In recent history the subject was transformed by one single event, the discovery, in 1912, by the German physicist, Max von Laue (1879-1960), that X-rays were diffracted by crystals. Not only did this demonstrate that X-rays belonged to a specific band of wavelengths in the electromagnetic spectrum, but it also established X-ray crystallography as one of the most useful methods of modern science. This linked one of the most ancient branches of science, crystallography, to one of the most modern, electromagnetic wave theory. Returning, first, to science as it was before this breakthrough, what, at the end of the day, is the defining characteristic of crystals? The answer was given by Henry Baker (1698-1774), who, after sketching dozens of crystalline substances observed with his microscope, noted how 'we see every Species working on a different plan, producing Cubes, Rhombs, Pyramids, Pentagons, Hexagons, Octagons, or some other curious figures, peculiar to itself. All these objects are geometrical solids, with plane faces, intersecting in straight lines. What is more, as noted by Aristotle, these curious shapes - which in any given crystal take only one form - must have the capacity to fill space.

This fundamental defining property of any crystal leads immediately to the geometry of three dimensions, a constant and often controversial leitmotiv of the whole history of crystallography. The basic principle is simple: the unit cell in any crystal system must be a parallelepiped, that is a solid with six faces, all of which are parallelograms, so that they divide up into three groups of two, with the two faces in each group being parallel. Subject to this limitation, there are seven possible crystal systems, of which the simplest is the cubic.

A system can be defined by the lengths of the sides converging at a single vertex, and the angles between them. Designating the former as  $a$ ,  $b$  and  $c$ , and the latter as  $\alpha$ ,  $\beta$  and  $\gamma$ , with  $\alpha$  being the angle between  $b$  and  $c$ ,  $\beta$ , that between  $c$  and  $a$ , and  $\gamma$ , that between  $a$  and  $b$ , the seven systems are as follows:

- (1) *cubic*:  $a = b = c$  and  $\alpha = \beta = \gamma = 90^\circ$ ,
- (2) *tetragonal*:  $a = b \neq c$  and  $\alpha = \beta = \gamma = 90^\circ$ ;
- (3) *orthorhombic*:  $a \neq b \neq c$  and  $\alpha = \beta = \gamma = 90^\circ$ ;
- (4) *hexagonal*:  $a = b \neq c$  and  $\alpha = \beta = \gamma \neq 90^\circ$ ;
- (5) *trigonal*:  $a = b \neq c$  and  $\alpha = \beta = \gamma \neq 90^\circ$ ;
- (6) *monoclinic*:  $a \neq b \neq c$  and  $\alpha = \gamma = 90^\circ \neq \beta$ ;
- (7) *triclinic*:  $a \neq b \neq c$  and  $\alpha \neq \beta \neq \gamma$ .

If this is thought of as being made of some elastic material - say India rubber - all possible crystalline forms can then be obtained by squashing it in different directions, but always in such a way that not only opposite faces but also the sides of each face remain parallel. Given this restriction, only the seven forms given above are possible. With the simplest form, the cube, all

faces are perfect squares and all angles are  $90^\circ$ . With the most complex, triclinic, all adjacent faces are different, as are the angles between them, none of which is  $90^\circ$ . Any uniform substance, will, if crystalline, contain only one form of crystal. (With aggregates, needless to say, any number of different forms are possible.)

The development of crystal systems to their present canonical form continued until well into the nineteenth century, by which time it had become clear that all known crystals (which are counted in thousands) belong to just one of them, and that this defines many distinctive properties of the individual crystal. It was only at the end of the eighteenth century that Lavoisier and others established that the constant repetition of definite geometrical figures was the essential defining principle, even though van Leeuwenhoek's microscopic investigations should have made this clear much earlier.

Huygens, even earlier, had established the fundamental crystallographic law that the constancy of interfacial angles comes from regular repetition. (In his *Treatise on Light*, published in 1690, he had noted how the same crystals found in France, Corsica and Iceland were completely identical). Huygens' measurements of interfacial angles were extremely accurate, and his examination of the Iceland crystal led to the first ever 'accurate mathematical analysis of the form of any crystalline substance', establishing also the importance of the crystal axis. These results were neglected for more than a century, simply because 'the faith of scientists in mathematics as their most potent tool and as the language of scientific expression was not yet so firmly entrenched that they were prepared to accept the fact that the wording could be extremely complex'. Where Kepler, after pages of complicated mathematics, was able to state his three laws of planetary motion in simple form, Huygens, in presenting his results with crystals, was unable to do likewise.

As the geometry of crystals became clearer, there was still constant debate as to whether they were linked to specific chemical forms, such as acids, alkalis or salts. Every such link had its own advocates, but in the end counter-examples were always found to disprove the case. On the other hand, from about 1720, it was clear that all metals were crystalline.

Another key question related to the forces that bound crystals together. The diverse properties of crystals made it difficult to establish a principle governing all cases. Many crystals are subject to cleavage, but only in certain directions, which explains why mica, for instance, can be reduced to very thin sheets (with countless experimental uses.) What force is it that binds mica in one direction but not in others? Any number of theories were put forward to answer this and other questions derived from particular properties - mechanical, optical, or whatever - of crystals. The great men of the day were at odds, so that Newton emphasised cohesive force where Huygens rejected this possibility. It is now known that 'the planes of cleavage... are those

across which the forces between the atoms are weakest' and that this 'may be due to the type of atomic bond or to a greater spacing of atoms or ions in the crystal at right angles to the plane of cleavage'. This, however, is the science of the twentieth century. There were still many bridges to cross to get to this point, although from the end of the eighteenth century it was generally accepted that the way molecules were superimposed within a crystal explained the different forms.

With countless instances of known crystals, by the end of the eighteenth century it had become clear that systematic classification was essential to real progress in understanding them. The history of science constantly shows how 'the development of comprehensive theoretical systems seems to be possible only after a preliminary classification of kinds has been achieved'. When it came to crystals, the problem was similarity of form among diverse substances combined with variation in shape in the same substance: how then were both the similarity and the diversity to be explained?

Classification characterises the mind-cast of the naturalist rather than that of the physicist, for where the former 'looks for the regularities of given forms' the latter 'seeks the form of given regularities'. It is not surprising, then, that Carolus Linnaeus (1707-78), famous for his system of botanical classification, also turned his hand to the 'minute and accurate description of the shapes of many crystals and explained in what ways certain configurations were related to or differed from others', nor that this led to his being called the founder of the science of crystallography.

The person responsible for this tribute was the Abbe Rene Just Haüy (1743-1882), to whom it might equally apply, were it not for the fact that almost all his fundamental theories in the end proved to be mistaken. Haüy came from a humble but devout provincial family that moved to Paris when he was seven years old. Although he trained for the priesthood, he also studied science, becoming a Master of Arts in 1761 long before becoming a priest in 1770.

As a scientist he started in botany, but a series of lectures in mineralogy at the Jardin du Roi turned his interest to crystallography. Inspiration came to him, so it is told, after he had dropped on to the floor a group of calcite minerals that had crystallised in the shape of hexagonal prisms. The fragments were rhombohedra, in precisely the shape of Iceland crystal, and following Archimedes (translated into French) he cried out 'tout est trouve'. What he claimed to have discovered was that rhombohedra must be the nuclei of all calcite crystals. This was actually rediscovery of a fact already quite well known, although not, apparently, to Haüy. In any case, he was set on the path of establishing the taxonomy of crystals according to an intricate scheme largely of his own devising.

Haüy's problem was that at a time when increasingly accurate measurements, using an instrument known as the goniometer, were being made of the

angles between crystal faces, he stuck to an elementary geometrical theory, which the new measurements failed to support. Haüy discovered through cleavage of a variety of substances that the number of different nuclei could be reduced to six primitive forms but in the end it all came to next to nothing. He persisted in his work during the period of the French Revolution, in which life for a priest was very uncertain, and he is still regarded as one of the first modern crystallographers. At the same time, the way in which his theories were faulted by others produced important results not only for crystallography but also for chemistry and optics. The three-dimensional geometry of crystals, depending on whichever of the seven crystal systems defines any given case, tells nothing of the number and ordering of molecules, atoms and ions, in each unit cell. However, the complete regularity of crystal structure, essential to Haüy's theory, means that whatever the pattern, it is repeated, like some three-dimensional wallpaper, in an indefinite series of lattices. The characteristic of any such series will in turn depend upon the direction, defined by an axis of the crystal, in which the lattices defining it are superimposed upon each other. This is critical for cleavage, which occurs where the bonding between the superimposed lattices is weak.

In the first half of the nineteenth century, a German chemist, Eilhardt Mitscherlich (1794-1863), was the first clearly to recognise a phenomenon known as a solid solution. This apparent contradiction in terms describes a compound solid in which ions of one chemical element may be substituted for another. This happens with certain alloys, as of gold and copper, but it also occurs with some so-called double salts. In any case the process only occurs in crystals: it is then a simple form of isomorphism, where chemically related substances take similar forms. Sometimes, the one element substitutes more or less at random for the other in the lattices, but in others, this occurs in a regular pattern, in which a series of superlattices is created. None of this fits in with Haüy's theoretical structure; nor does it fit the related phenomenon, also studied by Mitscherlich, of polymorphism. Haüy knew of Mitscherlich's work, but by never coming to terms with it ensured the eclipse of his own theory.

At least until 1912, the most interesting properties of crystals were optical. Some, such as double refraction, first noted in Iceland crystal by Erasmus Bartholin (1625-98) in 1669, had long been known, although - in spite of the interest of men such as Huygens and Newton - never explained. The optical properties all depend upon locating optical axes, of which there may be only one, in the crystal itself. The defining property of an axis of a crystal is symmetry, which means that if the crystal rotates about the axis, through a given angle, it will coincide with its previous position. A cube, for example, rotating about a line joining the centre points of two opposite faces, will achieve this result where the angle is  $90^\circ$ : this is the case of fourfold symmetry, since coincidence occurs four times in a complete rotation of  $360^\circ$ . In fact only two-, three-, four- and sixfold symmetry (for which the angles of rotation are  $180^\circ$ ,  $120^\circ$ ,  $90^\circ$  and  $60^\circ$ , respectively) are



possible if, as required, space is to be filled. The cubic system is unique in having the first three types of symmetry, and for each of them, the axes of rotation intersect at right angles. Such a system is isometric, and is the only in which double refraction does not occur. The cubic system, to which many crystals belong, alone has this property.

In crystals belonging to the other systems, either one or two of the axes are *optical*: an optical axis has the unique property of defining a direction in which light transmitted through the crystal is not subject to double refraction. Crystals belonging to tetragonal, hexagonal and trigonal systems have only one such axis, and are *uniaxial*: quartz and tourmaline are examples. Those belonging to rhombic, monoclinic and triclinic systems are *biaxial*: mica is the most familiar crystal with this property.

In the uniaxial case, a light ray not parallel to the optical axis, on entering the crystal divides into two rays that are polarised with the light waves at right angles to each other. The *ordinary* ray, so-called because it obeys the normal laws of refraction vibrates in a direction perpendicular to both the direction of propagation and the optical axis. The *extraordinary* ray, not subject to the normal laws of refraction, vibrates in a plane containing it and the optical axis, with the direction of vibration depending on the angle between the two. The biaxial case, although more complicated, is subject to similar rules relating to each of the two optical axes. The problem for Haüy was that his theory did not allow for the distinct optical status of either one or two of a crystal's axes.

Double refraction required Etienne Malus's (1775-1812) discovery of the polarisation of light in 1809, before it could be properly understood, which explains why Huygens', Newton's and Haüy's explanations all failed. Even so Malus failed to account for the difference between uniaxial and biaxial crystals, which had to await the discovery, by Jean-Baptiste Biot (1774-1862) of biaxiality in 1812. It is odd, in this context, that polarisation, which is fundamental to the understanding of light, took so long to be discovered, when it can so easily be demonstrated. This is because light incident on a plane mirror at an angle of some  $57^\circ$  becomes polarised on reflection, so that double reflection in two planes at right angles to each other will extinguish it. This means that the glare from a reflecting surface is partially polarised in the vertical plane (depending on how close the angle of reflection is to  $57^\circ$ ): Polaroid sun-glasses, based on a double refracting material that polarises light at right angles, then filter out some of the glare.

In 1756 the German physicist Franz Aepinus (1724-1802), experimenting with crystal tourmaline, discovered that opposite faces acquired polarised electric charges as the result of heating. This, the phenomenon of pyroelectricity, was a further demonstration of the importance of the crystal axis. This result was also known to Haüy, but his theory of crystal structure could not accommodate it. Haüy was greatly respected in his own lifetime, and Napoleon commissioned him to write a physics textbook to be used in all French *ly-*

ees: his discovery, at a relatively early stage, that crystals always break to produce rhomboidal fragments led to the formulation of the basic laws of crystallography. Haüy, however, made too much of a good thing and insisted on maintaining theoretical constructs, which, however simple and elegant, failed to hold up in the face of accurate observation of the crystalline phenomena described above.

Christian Weiss (1780-1856), having attained his doctorate at Leipzig when he was only twenty, became interested in mineralogy, and as a young man free to travel ended up in 1807 at the feet of Haüy in Paris. (He was already busy translating Haüy's *Traite de mineralogie* into German.) Haüy proved to be a tyrant, intolerant of any criticism, so that Weiss, on insisting on views which contradicted his own, was banished from his circle. No matter, Weiss returned to Leipzig as professor, and, under his direction, nineteenth-century crystallography 'became concerned with establishing the mathematical relationships evidenced in the crystalline end products of natural processes'. There he took the first steps to establishing the crystal systems as they are used today, but he was hesitant about accepting the possibility of symmetry systems in which the axes were not mutually perpendicular. Weiss's contemporary Friedrich Mohs (1773-1839), by grasping this particular nettle, established the present triclinic and mono-clinic crystal systems. According to Mohs, the main concern of crystallography was simply figured space, so that geometry should determine everything. The mathematics of symmetry became the main preoccupation of crystallographers. Chemistry could not be entirely disregarded, because Mitscherlich had shown that different substances could crystallise in the same form and the same substance in different forms.

Following Mohs' principles of classification, three types of symmetry combine to assign any crystal to one of the thirty-two possible classes or point groups, belonging to six crystal systems. Optical and electric properties of any crystal are then determined according to the class and system to which it belongs. Internal symmetry is constrained by the rule that any particle component is a node in a three-dimensional space lattice, so that all particles of a given type, say silicon atoms, have identical lattice environments.

In the course of the nineteenth century, fourteen different spaced lattices proved to be possible, each subject to two additional symmetry operations. Even so, Weiss's and Mohs' geometry told nothing about the shapes of the elements that were the basic constituents. The geometrical problem was finding the number of symmetrical ways of arranging points in space so the each one's environment was identical to those of the others, but not necessarily similarly ordered in the space lattice. Correlation between actual crystals with space groups led to a procedure with so many alternatives that a final solution to this problem defeated the nineteenth-century crystallographers. This had to wait until 1912, the year of one of the most far-reaching events in the history of scientific experiment - the

discovery of X-ray diffraction by the German physicist Max von Laue (1879-1960).

Although von Laue got most of the credit (and a Nobel prize two years later) the actual experiment was carried out by a research assistant and a doctoral candidate, who, by passing a narrow X-ray beam through a crystal of copper sulphate, recorded an image on a photographic plate. A similar image was obtained after substituting zinc blende. Von Laue then demonstrated that only the diffraction of very short electromagnetic waves by a regular arrangement of atoms or molecules in the crystal could account for this phenomenon. This could only mean that X-rays were part of the electromagnetic spectrum in the range  $10^{-11}$  to  $10^{-9}$  centimeters, because only these limits could be accommodated by the dimensions of the known particle structure of the crystals. Physicists, such as, notably, J. J. Thomson, had used X-rays in the laboratory ever since their discovery by Rontgen in 1895, but before von Laue's experiment their true nature was unknown. Oddly enough, von Laue himself almost immediately turned to other matters.

Even so, the importance of X-ray diffraction as a research tool was realised almost immediately. Its usefulness was much increased in 1913, when the American physicist William Coolidge (1873-1975) found a new method for producing X-rays, by directing accelerated electrons on to a metal target under a high vacuum. In 1916 he added another improvement: a hot tungsten cathode in place of a cold aluminium cathode. (The Coolidge tube is the prototype of all modern X-ray apparatus: its inventor, dying at 102, had nearly sixty years to enjoy its success.) Above all, a father and son team, William (1862-1942) and Lawrence Bragg (1890-1971) (who would share the Nobel prize for physics in 1915, a year after von Laue), using X-ray diffraction with their own improved 'Bragg' spectrometer determined the arrangement of atoms in common salt, pyrite, fluorite and calcite. This was only the beginning.

At the same time Lawrence stated the eponymous Bragg law, which related the wavelength of the X-rays to the separation distance of the layers of atoms forming the crystal planes and the angle of incidence of the X-rays. Crucially, the separation distance of the crystal planes is of the same microscopic order of length as the wavelength of the incident X-rays; if it were otherwise, there would be no diffraction. To a large extent, the Braggs' results confirmed the already established theory of the space lattice and groups described above, but even so X-ray crystallography, as an experimental technique, opened up whole new branches of science, such as solid-state physics (which relates to the electrical properties of semiconductors) and, at a later stage, molecular biology.

One man, more than any other, realised the full potential of this new field. This was Linus Pauling (1901-94), who went on to win two Nobel prizes - for chemistry in 1954 and peace in 1962.

Oregon, in 1901, was still something of a frontier state, and there Pauling was born, the first of the three children of an unsuccessful druggist, who would die in 1910. Although born in the depths of the countryside, Pauling grew up in Portland, the state's largest city. At Washington High School, he was remembered as being bright and very sure of himself: he left, however, without a diploma, after refusing to take a required course in civics.

This did not prevent him from gaining a place at the Oregon Agricultural College, where his fellow students were immediately taken by the ease with which he passed through first-year courses. He also published (in 1920) his first paper: there was little premonition of his future achievements in its title, 'The Manufacture of Cement in Oregon'. Once at college Pauling's ability was obviously noted by the professors, who in his third year offered him for \$100 a month a job as instructor for the second-year course in quantitative analysis that he had just taken himself. This was a life-saver, for Pauling had to support his gravely ill mother.

Although Pauling had thought of becoming a chemical engineer after graduation, in the course of his studies he set his sights on becoming a professional scientist. His special interests were in chemical bonding (the way in which atoms are bound into molecules, and molecules to each other) and the properties of crystals, such as hardness, cleavage and colour. Although Pauling's first choice for graduate study was the University of California at Berkeley, chance had it that he should go to the California Institute of Technology at Pasadena - long known, familiarly, as Caltech - the leading American research institute for chemical bonding. He arrived there, twenty-one years old, in September 1922.

Pauling's doctoral research would be on the structure of crystals, using the techniques of X-ray diffraction as developed by the Braggs in England. Pauling recorded the value of this technique, as he saw it at the end of his life, in these words: 'Our present understanding of the nature of the world of atoms, molecules, minerals and human beings can be attributed in large part to crystallography.' And no-one made better use of it than Pauling. But what then was he looking for?

Given Pauling's long life in science, this question has any number of answers. A key event was the discovery of quantum mechanics, mainly by physicists in Germany in 1925. A year later Pauling himself was in Germany, where he spent much of his time at the Institute of Theoretical Physics in Munich. Just as he arrived, in 1926, Erwin Schrodinger had published his key paper of wave mechanics, one particular aspect of quantum mechanics. Pauling reacted by investigating the chemical applications.

Before these developments, Bohr's theory of the elliptical orbits of electrons in atoms, with their capacity to be used in chemical bonding, was the last word in physical chemistry at the atomic level. This theory did not, however, go far enough: it clearly had potential for development, but the way

forward opened up in 1925 when a generation of young physicists, de Broglie, Heisenberg, Schrodinger, Dirac and Born, established quantum mechanics.

Pauling applied quantum mechanics to research into the structure and properties of substances, particularly crystals at least in the early days. He was particularly successful in investigating the two types of possible bonding, ionic and covalent, in silicate crystals. In the latter case, in which outer orbital electrons are shared between different atoms in a molecule, his methods led to a correct understanding of many basic substances, such as benzene and graphite. He adhered consistently to the principle, stated by Eddington in relation to physics, that science is a quest for structure rather than substance.

Pauling illustrated the point by comparing diamonds with graphite, both consisting only of carbon atoms. The palpable difference between the two is explained by the so-called quadrivalence of diamonds, in which every atom is bound to the four others closest to it in a regular pattern that defines the crystal (which belongs to a simple cubic or isometric system). It is characteristic of all hard substances that there are bonds connecting all the atoms in a crystal into one giant molecule. This is the case with quartz ( $\text{SiO}_2$ ), held together by strong silicon-oxygen bonds. Alternative arrangements produce mica, which splits into sheets, and asbestos, which splits into fibres. X-ray crystallography proved to be the ideal means of investigating such structures with unprecedented precision. Its scope as an investigative tool has transformed subjects, such as biochemistry, only remotely connected to crystallography. The complete mapping of the human genome, the most recent triumph of molecular biology, accords perfectly with the principles and practice of Pauling - one of the most creative minds of the twentieth century.

## PART II

### Mendeleev's periodic table

For more than a hundred years the periodic table has been an icon for chemistry, a status - to judge from the title of Primo Levi's *The Periodic Table* - extending far outside the discipline. For those who know how to read the table, which means almost any serious chemist, the key properties of the different elements (of which something over ninety occur in nature), systematically arranged in the order of their atomic weights, are immediately apparent. None the less, before its discovery in 1869 by Dimitry Ivanovich Mendeleev (1834-1907), the inchoate world of chemistry was only beginning to discover the order established by his table of elements.

The life of Mendeleev gives a distinctive Russian twist to the familiar story of the precocious schoolboy, who, after running through a gamut of academic distinctions, makes it to full professor at the age of thirty. His appearance, with gleaming eyes, long hair and an even longer beard, is that of a character from Tolstoy. This would fit in with his being born in Siberia. The city of Tobolsk, however, was far from being the back of beyond - at least, culturally. Mendeleev was the youngest of seventeen children. His father was the rector of the local gymnasium - equivalent to an English grammar school. The city was also home to a number of Decembrist exiles, so named because of the part they had played in the unsuccessful *coup d'etat* of December 1825, which was staged as part of the succession crisis of the death of Tsar Alexander I. This provided the city with an intelligentsia, whose presence brought contacts with metropolitan culture much appreciated within the Mendeleev family.

Unfortunately the rector became blind and lost his job when his youngest son was only a year old. The family was rescued by his wife, an intelligent and energetic woman, who took over and restored to prosperity a small family glass-works, mainly producing for pharmacists, in Arenzyanskoye, twenty miles outside Tobolsk. The youngest Mendeleev therefore grew up with molten glass, learning the trade from the craftsmen employed. In 1840, however, the family returned to Tobolsk so that he could go to school.

Although only six years old, Mendeleev soon proved to be a brilliant pupil in mathematics, physics and geography, although he hated Latin. In 1847 his father died, and his mother set off for Moscow with the younger children, travelling the whole way by coach. The object was to enrol the youngest, still only thirteen years old, in the university. He was rejected, because his gymnasium diploma from Tobolsk was not recognised. This meant another move, to the capital city, St. Petersburg, where Mendeleev was admitted to the Main Teacher Training College to study mathematics and the

natural sciences. He still could not escape misfortune: in 1850, when he was only sixteen, the deaths of both his mother and his older sister left him on his own.

In St. Petersburg Mendeleev did, however, have the advantage of being taught by a brilliant chemist, Professor Alexander Voskresensky, at a time when, following the work of Dalton and Berzelius, great advances were being made in the world of chemistry. In this favourable climate, Mendeleev completed major research into isomorphism, the process in which similar elements replace each other in some chemical combinations without changing their crystalline form.

This was significant for Mendeleev's future research, since 'the similarity of behaviour of atoms of different elements was ... one of the most important characteristics on the basis of which elements may be grouped in their natural order'. After taking his degree and winning a gold medal at the Main Teacher Training College in 1855, Mendeleev published his 'Isomorphism in Connection with Other Relations between Crystalline Forms and Chemical Constitutions' in 1856.

Like any young academic, Mendeleev looked for a job, preferring a location with a good climate because of ill-health. In Russia this meant the Black Sea coast: his first choice was Odessa, but a bureaucratic error led to another man being appointed there, so he ended up instead in Simferopol in the Crimea. The climate was just as good, but, because of war with the French and English (remembered by the latter for the Charge of the Light Brigade and Florence Nightingale), the university had closed Mendeleev's department. So as winter approached he took off for Odessa anyway, wearing a short fur coat, bearskin boots and a tall fur hat.

This turned out to be a good move: Mendeleev found a job at the local gymnasium that combined well with research at the Novorossiisk University. He wrote up his subject, specific volume, in a thesis presented to the University of St. Petersburg in 1856, which led to his being appointed reader in chemistry the following year. He was only twenty-three.

Mendeleev, clearly recognised as a high-flyer, soon gained permission to study abroad. His chosen destination was Heidelberg, already known for Bunsen and Kirchhoff's research into spectral analysis. However, in his two years in Germany (1857-59) he chose not to work in their shadow, preferring to research molecular cohesion in his own small laboratory. There he researched 'constant' gases, which, according to the prevailing wisdom, could never become liquid. Mendeleev's work on liquefaction and absolute boiling points showed that there were no such gases - a key result, long confirmed by the state of the art in low-temperature physics.

Only two years after returning to St. Petersburg Mendeleev published *Organic Chemistry* (1861), a revolutionary textbook. This work enunciated the key principle that 'every living phenomenon is the result not of some peculiar force or peculiar reason, but of the general laws of nature. There is not one living

process, taken separately, that may be attributed to a peculiar power.' This result may have been anticipated by Charles Darwin (whose *Origin of Species* was published in 1859), and Louis Pasteur was working towards it in France during the 1860s, but even so Mendeleev was ahead of his times. (Not surprisingly his outspoken materialism would later commend him to Soviet scientists.) During the 1860s Mendeleev also worked on solutions, reaching the paradoxical conclusion that their properties (density, conductivity, etc.) 'change in leaps against the background of the general steady change in the proportions of the components of the solutions'. This followed from tests made with 283 different substances, with the changes always taking place at 'specific points', whose study became critical in physical chemistry.

In 1862 Mendeleev, seldom lucky in family life, made an unhappy marriage to Feozva Leshcheva, who never showed the interest and support that a Russian of his generation expected from a wife. In 1876 he got a divorce, having met his true love, Anna Popova. His marriage to her in 1880 transformed his home into a salon open to the scientists of the day. Under Russian law, however, it was bigamous, since less than seven years had elapsed since the divorce. The Tsar, informed of this lapse, observed, 'Mendeleev may have two wives, but Russia has only one Mendeleev.'

In 1867 Mendeleev, still only thirty-three, succeeded Voskresensky to the top chair at St. Petersburg, where his lectures, in which he would often 'digress into mechanics, physics, astronomy cosmogony, meteorology, geology, the physiology of animals and plants, agronomy and also into different branches of technology, including air navigation and artillery', were greeted with rapture.

To meet the needs of his students, Mendeleev started working on a general manual for chemistry. Trying to establish a basic principle for systematising chemical knowledge by comparing atomic weights, Mendeleev concluded that 'the properties of the elements are in periodic dependence on their atomic weights'. This fundamental insight came to him in a dream on 17 February 1869; he had taken a brief nap while working on his book, and 'when he awoke, he set out the chart, in virtually its final form'.

Mendeleev's table of elements was presented to the new Russian Chemical Society on 18 March 1869. The fundamental law was then stated in his *Foundations of Chemistry*, published later in the year and described by Mendeleev as 'his favourite child', and *An Outline of the System of the Elements* was circulated outside, as a pamphlet, in 1870.

Mendeleev knew of 61 separate elements: these could be ordered according to their increasing atomic weights. This was clearly the starting point for any systematic classification. Elements could also be classified according to their properties, so that the alkali metals (e.g. sodium and potassium) belonged together, as did the alkaline earth elements (e.g. magnesium and calcium) and, at the other extreme, the non-metallic halogens (e.g. chlorine and iodine).



The periodic table then shows how, with the increase in atomic weight, elements at first acquire entirely new, changing properties, and then how these properties recur in a new period, in a new line and row of the elements and in the same sequence as in the preceding row. Thus the law of periodicity may be expressed as follows: the properties of the elements, and thus the properties of simple or compound bodies of these elements, are dependent in a periodic way on the magnitude of the atomic weight of the elements.

In compiling the periodic table Mendeleev faced four different problems (although the last remained hidden from him). First, nine of the atomic weights in the records were incorrect, so that that of beryllium was recorded as 13.7 instead of 9, and that of calcium as 20 instead of 40. Mendeleev made the necessary corrections, as he did also with gold, platinum, osmium, iridium, yttrium, indium and erbium. In all these cases the fault lay with inaccurate work done by others earlier in the century.

Second, if there was any regularity in the rate of increase, then there were at least six gaps in the table. These in fact represented as yet undiscovered elements. That three of the gaps related closely to boron, aluminium and silicon in the periodic system led Mendeleev to name the missing elements eka-boron, eka-aluminium and eka-silicon - *eka* being the Sanskrit for 'one'.

In 1875 a French chemist, Lecoq de Boisbaudran (1838-1912), in a spectral analysis of zinc blende from a mine in the Pyrenees, noted the presence of an unknown element, whose properties corresponded to those of eka-aluminium predicted by Mendeleev. De Boisbaudran, patriotically minded, named the newly discovered element 'gallium'. Its discovery led to something of a dispute between the Academic des Sciences in Paris and the Russian Physical-Chemical Society. Mendeleev immediately saw his own prediction confirmed, but while de Boisbaudran's atomic weight, 68, was acceptable, his measure of density, at 4.7, was inconsistent with the value, predicted according to the periodic system, of 5.9. Both sides stuck to their guns, but in the end Mendeleev was proved right (although, ironically, the undisputed number for atomic weight was to prove to be too low).

Mendeleev had an easier ride with eka-boron and eka-silicon: the former, isolated by a Swedish chemist in 1879, was appropriately named 'scandium'; the latter was named 'germanium' after being isolated by Clemens Winkler (1838-1904) in 1886. Internationally this was an important breakthrough for the periodic system, since, for the second time, Mendeleev's predicted values for atomic weight and density had independently proved correct - as was immediately recognised and acknowledged by the finders in both cases. Moreover, Winkler's germanium would dissolve in water but not in acids, had an oxidization formula  $\text{GeO}_2$ , and produced a chlorine compound,  $\text{GeCl}_4$ , with a boiling point of  $83^\circ\text{C}$  and a specific weight of 1.887 - in near perfect accord with Mendeleev's predictions.

Mendeleev's third problem was that if the classification in the columns was to be consistent with what his system required, then tellurium and iodine

should change places, as should cobalt and nickel, even though this would reverse the order based on atomic weight. Mendeleev made the necessary changes, but the full explanation as to why they were correct had to await the discovery in 1913, six years after his death, of atomic numbers by Henry Moseley (1887-1915).

The fourth problem was somewhat esoteric: although never suspected by Mendeleev, there were gaps at the end of every row in the table, so that, moving to the next row from fluorine, chlorine, bromine and iodine in column 7 led directly to sodium, potassium, rubidium and caesium in column 1. (Note how the respective suffixes, 'ine' and 'ium' reflect the common properties of the elements in the two columns; this is the whole point to the periodic table). Mendeleev might have noted in all these cases a relatively large increment, of the order of 4 or 5 (where otherwise there is a maximum of about 3) in atomic weight, but, if so, he did not realise its significance.

### John Dalton

#### A New System of Chemical Philosophy.

*A New System of Chemical Philosophy. London: R.Bickerstaff, 1808-27.*

#### On the Constitution of Solids

A solid body is one, the particles of which are in a state of equilibrium betwixt two great powers, attraction and repulsion, but in such a manner, that no change can be made in their distances without considerable force. If an approximation of the particles is attempted by force, then the heat resists it; if a separation, then the attraction resists it. The notion of Boscovich of alternating planes of attraction and repulsion seems unnecessary; except that upon forcibly breaking the cohesion of any body, the newly exposed surface must receive such a modification in its atmosphere of heat, as may prevent the future junction of the parts, without great force.

The essential distinction between liquids and solids, perhaps consists in this, that heat changes the figure of arrangement of the ultimate particles of the former continually and gradually, whilst they retain their liquid form; whereas in the latter, it is probable, that change of temperature does no more than change the size, and not the arrangement of the ultimate particles.

Notwithstanding the *hardness* of solid bodies, or the difficulty of moving the particles one amongst another, there are several that admit of such motion without fracture, by the application of proper force, especially if assisted by heat. The ductility and malleability of the metals, need only to be mentioned. It should seem the particles glide along each others surface, somewhat like a piece of polished iron at the end of a magnet, without being at all weakened in their cohesion. The absolute force of cohesion, which constitutes the *strength* of bod-

ies, is an enquiry of great practical importance. It has been found by experiment, that wires of the several metals beneath, being each  $1/10$  of an inch in diameter, were just broken by the annexed weights.

Lead.....	29 1/4	
Tin.....	49 1/4	
Copper.....	299 1/4	
Brass.....	360	} Pounds.
Silver.....	370	
Iron.....	450	
Gold.....	500	

A piece of good oak, an inch square and a yard long, will just bear in the middle 330 lbs. But such a piece of wood should not in practice be trusted, for any length of time, with above  $1/3$  or  $1/4$  of that weight. Iron is about 10 times as strong as oak, of the same dimensions.

One would be apt to suppose that *strength* and *hardness* ought to be found proportionate to each other; but this is not the case. Glass is harder than iron, yet the latter is much the stronger of the two.

Crystallization exhibits to us the effects of the natural arrangement of the ultimate particles of various compound bodies; but we are scarcely yet sufficiently acquainted with chemical synthesis and analysis to understand the rationale of this process. The rhomboidal form may arise from the proper position of 4, 6, 8 or 9 globular particles, the cubic form from 8 particles, the triangular form from 3, 6 or 10 particles, the hexahedral prism from 7 particles, etc. Perhaps, in due time, we may be enabled to ascertain the number and order of elementary particles, constituting any given compound element, and from that determine the figure which it will prefer on crystallization, and *vice versa*; but it seems premature to form any theory on this subject, till we have discovered from other principles the number and order of the primary elements which combine to form some of the compound elements of most frequent occurrence.

### On Chemical Synthesis

When any body exists in the elastic state, its ultimate particles are separated from each other to a much greater distance than in any other state; each particle occupies the centre of a comparatively large sphere, and supports its dignity by keeping all the rest, which by their gravity, or otherwise are disposed to encroach up it, at a respectful distance. When we attempt to conceive the *number* of particles in an atmosphere, it is somewhat like attempting to conceive the number of stars in the universe; we are confounded with the thought. But if we limit the subject, by taking a given volume of any gas, we seem persuaded that,

let the divisions be ever so minute, the number of particles must be finite; just as in a given space of the universe, the number of stars and planets cannot be infinite.

Chemical analysis and synthesis go no farther than to the separation of particles one from another, and to their reunion. 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. All the changes we can produce, consist in separating particles that are in a state of cohesion or combination, and joining those that were previously at a distance.

In all chemical investigations, it has justly been considered an important object to ascertain the relative *weights* of the simples which constitute a compound. But unfortunately the enquiry has terminated here; whereas from the relative weights in the mass, the relative weights of the ultimate particles or atoms of the bodies might have been inferred, from which their number and weight in various other compounds would appear, in order to assist and to guide future investigations, and to correct their results. Now it is one great object of this work, to shew the importance and advantage of ascertaining *the relative weights of the ultimate particles, both of simple and compound bodies, the number of simple elementary particles which constitute one compound particle, and the number of less compound particles which enter into the formation of one more compound particle.*

If there are two bodies, A and B, which are disposed to combine, the following is the order in which the combinations may take place, beginning with the most simple: namely,

*1 atom of A + 1 atom of B = 1 atom of C, binary.*

*1 atom of A + 2 atoms of B = 1 atom of D, ternary.*

*2 atoms of A + 1 atom of B = 1 atom of E, ternary.*

*1 atom of A + 3 atoms of B = 1 atom of F, quaternary.*

*3 atoms of A + 1 atom of B = 1 atom of G, quaternary. etc. etc.*

The following general rules may be adopted as guides in all our investigations respecting chemical synthesis.

1st. When only one combination of two bodies can be obtained, it must be presumed to be a *binary* one, unless some cause appear to the contrary.

2d. When two combinations are observed, they must be presumed to be a *binary* and a *ternary*.

3d. When three combinations are obtained, we may expect one to be a *binary*, and the other two *ternary*.

4th. When four combinations are observed, we should expect one *binary*, two *ternary*, and one *quaternary*, etc.

5th. A *binary* compound should always be specifically heavier than the mere mixture of its two ingredients.

6th. A *ternary* compound should be specifically heavier than the mixture of a *binary* and a *simple*, which would, if combined, constitute it; etc.

7th. The above rules and observations equally apply, when two bodies, such as C and D, D and E, etc. are combined.

From the application of these rules, to the chemical facts already well ascertained, we deduce the following conclusions; 1st. That water is a *binary* compound of hydrogen and oxygen, and the relative weights of the two elementary atoms are as 1 : 7, nearly; 2d. That ammonia is a *binary* compound of hydrogen and azote, and the relative weights of the two atoms are as 1 : 5, nearly; 3d. That nitrous gas is a *binary* compound of azote and oxygen, the atoms of which weigh 5 and 7 respectively; that nitric acid is a *binary* or *ternary* compound according as it is derived, and consists of one atom of azote and two of oxygen, together weighing 19; that nitrous oxide is a compound similar to nitric acid, and consists of one atom of oxygen and two of azote, weighing 17; that nitrous acid is a *binary* compound of nitric acid and nitrous gas, weighing 31; that oxynitric acid is a *binary* compound of nitric acid and oxygen, weighing 26; 4th. That carbonic oxide is a *binary* compound, consisting of one atom of charcoal, and one of oxygen, together weighing nearly 12; that carbonic acid is a *ternary* compound, (but sometimes *binary*) consisting of one atom of charcoal, and two of oxygen, weighing 19; etc. etc. In all these cases the weights are expressed in atoms of hydrogen, each of which is denoted by unity.

In the sequel, the facts and experiments from which these conclusions are derived, will be detailed; as well as a great variety of others from which are inferred the constitution and weight of the ultimate particles of the principal acids, the alkalis, the earths, the metals, the metallic oxides and sulphurets, the long train of neutral salts, and in short, all the chemical compounds which have hitherto obtained a tolerably good analysis. Several of the conclusions will be supported by original experiments.

From the novelty as well as importance of the ideas suggested in this chapter, it is deemed expedient to give plates, exhibiting the mode of combination in some of the more simple cases. A specimen of these accompanies this first part. The elements or atoms of such bodies are conceived at present to be simple, are denoted by a small circle, with some distinctive mark; and the combinations consist in the juxta-position of two or more of these; when three or more particles of elastic fluids are combined together in one, it is to be supposed that the particles of the same kind repel each other, and therefore take their stations accordingly.

## Michael Faraday

### Chemical History of a Candle to Which is Added A Lecture on Platinum.

*Chemical History of a Candle to Which is Added A Lecture on Platinum. Edited by William Crookes. London: Griffin, Bohn, and Company, 1861.*

#### Carbon or Charcoal—Coal Gas—Respiration and its Analogy to the Burning of a Candle—Conclusion.

A Lady who honours me by her presence at these lectures, has conferred a still further obligation by sending me these two candles, which are from Japan, and, I presume, are made of that substance to which I referred in a former lecture. You see that they are even far more highly ornamented than the French candles, and, I suppose, are candles of luxury, judging from their appearance. They have a remarkable peculiarity about them; namely, a hollow wick,—that beautiful peculiarity which Argand introduced into the lamp and made so valuable. To those who receive such presents from the East, I may just say that this and such like materials, gradually undergo a change which gives them on the surface a dull and dead appearance; but they may easily be restored to their original beauty if the surface be rubbed with a clean cloth or silk handkerchief, so as to polish the little rugosity or roughness: this will restore the beauty of the colours. I have so rubbed one of these candles, and you see the difference between it and the other which has not been polished, but which may be restored by the same process. Observe, also, that these moulded candles from Japan are made more conical than the moulded candles in this part of the world.

I told you, when we last met, a good deal about carbonic acid. We found by the lime-water test, that when the vapour from the top of the candle or lamp was received into bottles and tested by this solution of lime-water (the composition of which I explained to you, and which you can make for yourselves), we had that white opacity which was in fact calcareous matter, like shells and corals, and many of the rocks and minerals in the earth. But I have not yet told you fully and clearly the chemical history of this substance, carbonic acid, as we have it from the candle, and I must now resume that subject. We have seen the products, and the nature of them, as they issue from the candle. We have traced the water to its elements, and now we have to see where are the elements of the carbonic acid supplied by the candle: a few experiments will show this. You remember that when a candle burns badly it produces smoke; but if it is burning well, there is no smoke. And you know that the brightness of the candle is due to this smoke, which becomes ignited. Here is an experiment to prove this: so long as the smoke remains in the flame of the candle and becomes ignited it gives a beautiful light, and never appears to us in the form of black particles. I will light some fuel, which is extravagant in its burning; this will serve our purpose—a little turpentine on a sponge. You see the smoke rising from it, and floating into the air in large quantities; and remember now, the carbonic acid that we have

from the candle is from such smoke as that. To make that evident to you, I will introduce this turpentine burning on the sponge into a flask where I have plenty of oxygen, the rich part of the atmosphere, and you now see that the smoke is all consumed. This is the first part of our experiment, and now what follows? The carbon which you saw flying off from the turpentine flame in the air is now entirely burned in this oxygen, and we shall find that it will, by this rough and temporary experiment, give us exactly the same conclusion and result as we had from the combustion of the candle. The reason why I make the experiment in this manner is solely that I may cause the steps of our demonstration to be so simple that you can never for a moment lose the train of reasoning, if you only pay attention. All the carbon which is burned in oxygen, or air, comes out as carbonic acid, whilst those particles which are not so burned show you the second substance in the carbonic acid; namely, the carbon—that body which made the flame so bright whilst there was plenty of air, but which was thrown off in excess when there was not oxygen enough to burn it.

I have also to show you a little more distinctly, the history of carbon and oxygen in their union to make carbonic acid. You are now better able to understand this than before, and I have prepared three or four experiments by way of illustration. This jar is filled with oxygen, and here is some carbon which has been placed in a crucible, for the purpose of being made red-hot. I keep my jar dry, and venture to give you a result imperfect in some degree, in order that I may make the experiment brighter. I am about to put the oxygen and the carbon together. That this is carbon (common charcoal pulverized) you will see by the way in which it burns in the air [letting some of the red-hot charcoal fall out of the crucible]. I am now about to burn it in oxygen gas, and look at the difference. It may appear to you at a distance as if it were burning with a flame; but it is not so. Every little piece of charcoal is burning as a spark, and whilst it so burns it is producing carbonic acid. I specially want these two or three experiments to point out what I shall dwell upon more distinctly by and by—that carbon burns in this way, and not as a flame.

Instead of taking many particles of carbon to burn I will take a rather large piece, which will enable you to see the form and size, and to trace the effects very decidedly. Here is the jar of oxygen, and here is the piece of charcoal, to which I have fastened a little piece of wood, which I can set fire to, and so commence the combustion, which I could not conveniently do without. You now see the charcoal burning, but not as a flame (or if there be a flame it is the smallest possible one, which I know the cause of; namely, the formation of a little carbonic oxide close upon the surface of the carbon). It goes on burning, you see, slowly producing carbonic acid by the union of this carbon or charcoal (they are equivalent terms) with the oxygen. I have here another piece of charcoal, a piece of bark, which has the quality of being blown to pieces—exploding—as it burns. By the effect of the heat we shall reduce the lump of carbon into particles that will fly off; still every particle, equally with the whole mass, burns in this

peculiar way—it burns as a coal and not like a flame. You observe a multitude of little combustions going on, but no flame. I do not know a finer experiment than this to show that carbon burns with a spark.

Here, then, is carbonic acid formed from its elements. It is produced at once; and if we examined it by lime-water, you will see that we have the same substance which I have previously described to you. By putting together 6 parts of carbon by weight (whether it comes from the flame of a candle or from powdered charcoal) and 16 parts of oxygen by weight, we have 22 parts of carbonic acid; and, as we saw last time, the 22 parts of carbonic acid combined with 28 parts of lime, produced common carbonate of lime. If you were to examine an oyster-shell and weigh the component parts, you would find that every 50 parts would give 6 of carbon and 16 of oxygen combined with 28 of lime. However, I do not want to trouble you with these minutiae; it is only the general philosophy of the matter that we can now go into. See how finely the carbon is dissolving away [pointing to the lump of charcoal burning quietly in the jar of oxygen]. You may say that the charcoal is actually dissolving in the air round about; and if that were perfectly pure charcoal, which we can easily prepare, there would be no residue whatever. When we have a perfectly cleansed and purified piece of carbon, there is no ash left. The carbon burns as a solid dense body, that heat alone cannot change as to its solidity, and yet it passes away into vapour that never condenses into solid or liquid under ordinary circumstances; and what is more curious still is the fact that the oxygen does not change in its bulk by the solution of the carbon in it. Just as the bulk is at first, so it is at last, only it has become carbonic acid.

There is another experiment which I must give you before you are fully acquainted with the general nature of carbonic acid. Being a compound body, consisting of carbon and oxygen, carbonic acid is a body that we ought to be able to take asunder. And so we can. As we did with water, so we can with carbonic acid,—take the two parts asunder. The simplest and quickest way is to act upon the carbonic acid by a substance that can attract the oxygen from it, and leave the carbon behind. You recollect that I took potassium and put it upon water or ice, and you saw that it could take the oxygen from the hydrogen. Now, suppose we do something of the same kind here with this carbonic acid. You know carbonic acid to be a heavy gas: I will not test it with lime-water, as that will interfere with our subsequent experiments, but I think the heaviness of the gas and the power of extinguishing flame will be sufficient for our purpose. I introduce a flame into the gas, and you will see whether it will be put out. You see the light is extinguished. Indeed, the gas may, perhaps, put out phosphorus, which you know has a pretty strong combustion. Here is a piece of phosphorus heated to a high degree. I introduce it into gas, and you observe the light is put out, but it will take fire again in the air, because there it re-enters into combustion. Now let me take a piece of potassium, a substance which even at common temperatures can act upon carbonic acid, though not sufficiently for our present purpose, be-



cause it soon gets covered with a protecting coat; but if we warm it up to the burning point in air, as we have a fair right to do, and as we have done with phosphorus, you will see that it can burn in carbonic acid; and if it burns, it will burn by taking oxygen, so that you will see what is left behind. I am going, then, to burn this potassium in the carbonic acid, as a proof of the existence of oxygen in the carbonic acid. [In the preliminary process of heating the potassium exploded.] Sometimes we get an awkward piece of potassium that explodes, or something like it, when it burns. I will take another piece, and now that it is heated I introduce it into the jar, and you perceive that it burns in the carbonic acid—not so well as, in the air, because the carbonic acid contains the oxygen combined, but it does burn, and takes away the oxygen. If I now put this potassium into water, I find that besides the potash formed (which you need not trouble about) there is a quantity of carbon produced. I have here made the experiment in a very rough way, but I assure you that if I were to make it carefully, devoting a day to it, instead of five minutes, we should get all the proper amount of charcoal left in the spoon, or in the place where the potassium was burned, so that there could be no doubt as to the result. Here, then, is the carbon obtained from the carbonic acid, as a common black substance; so that you have the entire proof of the nature of carbonic acid as consisting of carbon and oxygen. And now, I may tell you, that *whenever* carbon burns under common circumstances, it produces carbonic acid.

Suppose I take this piece of wood, and put it into a bottle with lime-water. I might shake that lime-water up with wood and the atmosphere as long as I pleased, it would still remain clear as you see it; but suppose I burn the piece of wood in the air of that bottle. You, of course, know I get water. Do I get carbonic acid? [The experiment was performed.] There it is, you see—that is to say, the carbonate lime, which results from carbonic acid, and that carbonic acid must be formed from the carbon which comes from the wood, from the candle, or any other thing. Indeed, you have yourselves frequently tried a very pretty experiment, by which you may see the carbon in wood. If you take a piece of wood, and partly burn it, and then blow it out, you have carbon left. There are things that do not show carbon in this way. A candle does not so show it, but it contains carbon. Here also is a jar of coal-gas, which produces carbonic acid abundantly,—you do not see the carbon, but we can soon show it to you. I will light it, and as long as there is any gas in this cylinder it will go on burning. You see no carbon, but you see a flame, and because that is bright it will lead you to guess that there is carbon in the flame. But I will show it to you by another process. I have some of the same gas in another vessel, mixed with a body that will burn the hydrogen of the gas, but will not burn the carbon. I will light them with a burning taper, and you perceive the hydrogen is consumed, but not the carbon, which is left behind as a dense black smoke. I hope that by these three or four experiments you will learn to see when carbon is present, and understand what

are the products of combustion, when gas or other bodies are thoroughly burned in the air.

Before we leave the subject of carbon, let us make a few experiments and remarks upon its wonderful condition, as respects ordinary combustion. I have shown you that the carbon in burning burns only as a solid body, and yet you perceive that, after it is burned, it ceases to be a solid. There are very few fuels that act like this. It is in fact only that great source of fuel, the carbonaceous series, the coals, charcoals, and woods, that can do it. I do not know that there is any other elementary substance besides carbon that burns with these conditions; and if it had not I been so, what would happen to us? Suppose all fuel had been like iron which, when it burns, it burns into a solid substance. We could not then have such a combustion as you have in this fireplace. Here also is another kind of fuel which burns very well—as well as, if not better, than carbon—so well, indeed, as to take fire of itself when it is in the air, as you see. [Breaking a tube full of lead pyrophorus.] This substance is lead, and you see how wonderfully combustible it is. It is very much divided, and is like a heap of coals in the fire-place: the air can get to its surface and inside, and so it burns. But why does it not burn in that way now when it is lying in a mass? [Emptying the contents of the tube in a heap on to a plate of iron.] Simply because the air cannot get to it. Though it can produce a great heat, the great heat which we want in our furnaces and under our boilers, still that which is produced cannot get away from the portion which remains unburned underneath, and that portion, therefore, is prevented from coming in contact with the atmosphere, and cannot be consumed. How different is that from carbon! Carbon burns just in the same way as this lead does, and so gives an intense fire in the furnace, or wherever you choose to burn it; but then the body produced by its combustion passes away, and the remaining carbon is left clear. I showed you how carbon went on dissolving in the oxygen, leaving no ash; whereas, here [pointing to the heap of pyrophorus] we have actually more ash than fuel, for it is heavier by the amount of the oxygen which has united with it. Thus you see the difference between carbon and lead or iron: if we chose iron, which gives so wonderful a result in our applications of this fuel, either as light or heat. If, when the carbon burnt, the product went off as a solid body, you would have had the room filled with an opaque substance, as in the case of the phosphorus; but when carbon burns, everything passes up into the atmosphere. It is in a fixed, almost unchangeable condition before the combustion; but afterwards it is in the form of gas, which it is very difficult (though we have succeeded) to produce in a solid or liquid state.

Now I must take you to a very interesting part of our subject—to the relation between the combustion of a candle and that living kind of combustion which goes on within us. In every one of us there is a living process of combustion going on very similar to that of a candle, and I must try to make that plain to you. For it is not merely true in a poetical sense—the relation of the life of man to a taper; and if you will follow, I think I can make this clear. In order to make

the relation very plain, I have devised a little apparatus which we can soon build up before you. Here is a board and a groove cut in it, and I can close the groove at the top part by a little cover; I can then continue the groove as a channel by a glass tube at each end, there being a free passage through the whole. Suppose I take a taper or candle (we can now be liberal in our use of the word "candle," since we understand what it means), and place it in one of the tubes; it will go on, you see, burning very well. You observe that the air which feeds the flame passes down the tube at one end, then goes along the horizontal tube, and ascends the tube at the other end in which the taper is placed. If I stop the aperture through which the air enters, I stop combustion, as you perceive. I stop the supply of air, and consequently the candle goes out. But now what will you think of this fact? In a former experiment I showed you the air going from one burning candle to a second candle. If I took the air proceeding from another candle, and sent it down by a complicated arrangement into this tube, I should put this burning candle out. But what will you say when I tell you that my breath will put out that candle? I do not mean by blowing at all, but simply that the nature of my breath is such that a candle cannot burn in it. I will now hold my mouth over the aperture, and without blowing the flame in any way, let no air enter the tube but what comes from my mouth. You see the result. I did not blow the candle out. I merely let the air which I expired pass into the aperture, and the result was that the light went out for want of oxygen, and for no other reason. Something or other—namely, my lungs—had taken away the oxygen from the air, and there was no more to supply the combustion of the candle. It is, I think, very pretty to see the time it takes before the bad air which I throw into this part of the apparatus has reached the candle. The candle at first goes on burning, but so soon as the air has had time to reach it goes out. And now I will show you another experiment, because this is an important part of our philosophy. Here is a jar which contains fresh air, as you can see by the circumstance of a candle or gas-light burning it. I make it close for a little time, and by means of a pipe I get my mouth over it so that I can inhale the air. By putting it over water, in the way that you see, I am able to draw up this air (supposing the cork to be quite tight), take it into my lungs, and throw it back into the jar: we can then examine it, and see the result. You observe, I first take up the air, and then throw it back, as is evident from the ascent and descent of the water, and now, by putting a taper into the air, you will see the state in which it is by the light being extinguished. Even one inspiration, you see, has completely spoiled this air, so that it is no use my trying to breathe it a second time. Now you understand the ground of the impropriety of many of the arrangements among the houses of the poorer classes, by which the air is breathed over and over again, for the want of a supply, by means of proper ventilation, sufficient to produce a good result. You see how bad the air becomes by a single breathing; so that you can easily understand how essential fresh air is to us.

To pursue this a little further, let us see what will happen with lime-water. Here is a globe which contains a little lime-water, and it is so arranged as regards the pipes, as to give access to the air within, so that we can ascertain the effect of respired, or unrespired air upon it. Of course I can either draw in air, and so make the air that feeds my lungs go through the lime-water, or I can force the air out of my lungs through the tube, which goes to the bottom, and so show its effect upon the lime-water. You will observe that however long I draw the external air into the lime-water, and then through it to my lungs, I shall produce no effect upon the water—it will not make the lime-water turbid; but if I throw the air *from* my lungs through the lime-water, several times in succession, you see how white and milky the water is getting, showing the effect which expired air has had upon it; and now you begin to know that the atmosphere which we have spoiled by respiration is spoiled by carbonic acid, for you see it here in contact with the lime-water.

I have here two bottles, one containing lime-water and the other common water, and tubes which pass into the bottles and connect them. The apparatus is very rough, but it is useful notwithstanding. If I take these two bottles, inhaling here and exhaling there, the arrangement of the tubes will prevent the air going backwards. The air coming in will go to my mouth and lungs, and in going out, will pass through the lime-water, so that I can go on breathing and making an experiment, very refined in its nature, and very good in its results. You will observe that the good air has done nothing to the lime-water; in the other case nothing has come to the lime-water but my respiration, and you see the difference in the two cases.

Let us now go a little further. What is all this process going on within us which we cannot do without, either day or night, which is so provided for by the Author of all things that He has arranged that it shall be independent of all will? If we restrain our respiration, as we can to a certain extent, we should destroy ourselves. When we are asleep, the organs of respiration and the parts that are associated with them, still go on with their action, so necessary is this process of respiration to us, this contact of the air with the lungs. I must tell you, in the briefest possible manner, what this process is. We consume food: the food goes through that strange set of vessels and organs within us, and is brought into various parts of the system, into the digestive parts especially; and alternately the portion which is so changed is carried through our lungs by one set of vessels, while the air that we inhale and exhale is drawn into and thrown out of the lungs by another set of vessels, so that the air and the food come close together, separated only by an exceedingly thin surface: the air can thus act upon the blood by this process, producing precisely the same results in kind as we have seen in the case of the candle. The candle combines with parts of the air, forming carbonic acid, and evolves heat; so in the lungs there is this curious, wonderful change taking place. The air entering, combines with the carbon (not carbon in a free state, but, as in this case, placed ready for action at the moment), and makes car-

bonic acid, and is so thrown out into the atmosphere, and thus this singular result takes place; we may thus look upon the food as fuel. Let me take that piece of sugar, which will serve my purpose. It is a compound of carbon, hydrogen, and oxygen, similar to a candle, as containing the same elements, though not in the same proportion; the proportions being as shown in this table:—

*Sugar.*

Carbon.....	72	
Hydrogen.....	11	} 99
Oxygen.....	88	

This is, indeed a very curious thing, which you can well remember, for the oxygen and hydrogen are in exactly the proportions which form water, so that sugar may be said to be compounded of 72 parts of carbon and 99 parts of water; and it is the carbon in the sugar that combines with the oxygen carried in by the air in the process of respiration, so making us like candles; producing these actions, warmth, and far more wonderful results besides, for the sustenance of the system, by a most beautiful and simple process. To make this still more striking, I will take a little sugar; or to hasten the experiment I will use some syrup, which contains about three-fourths of sugar and a little water. If I put a little oil of vitriol on it, it takes away the water, and leaves the carbon in a black mass. [The Lecturer mixed the two together.] You see how the carbon is coming out, and before long we shall have a solid mass of charcoal, all of which has come out of sugar. Sugar, as you know, is food, and here we have absolutely a solid lump of carbon where you would not have expected it. And if I make arrangements so as to oxidize the carbon of sugar, we shall have a much more striking result. Here is sugar, and I have here an oxidizer—a quicker one than the atmosphere; and so we shall oxidize this fuel by a process different from respiration in its form, though not different in its kind. It is the combustion of the carbon by the contact of oxygen which the body has supplied to it. If I set this into action at once, you will see combustion produced. Just what occurs in my lungs—taking in oxygen from another source, namely, the atmosphere, takes place here by a more rapid process.

You will be astonished when I tell you what this curious play of carbon amounts to. A candle will burn some four, five, six, or seven hours. What then must be the daily amount of carbon going up into the air in the way of carbonic acid! What a quantity of carbon must go from each of us in respiration! What a wonderful change of carbon must take place under these circumstances of combustion or respiration! A man in twenty-four hours converts as much as seven ounces of carbon into carbonic acid; a milch cow will convert seventy ounces, and a horse seventy-nine ounces, solely by the act of respiration. That is, the horse in twenty-four hours burns seventy-nine ounces of charcoal, or carbon, in his organs of respiration to supply his natural warmth in that time. All the warm-

blooded animals get their warmth in this way, by the conversion of carbon, not in a free state, but in a state of combination. And what an extraordinary notion this gives us of the alterations going on in our atmosphere. As much as 5,000,000 pounds, or 548 tons, of carbonic acid is formed by respiration in London alone in twenty-four hours. And where does all this go? Up into the air. If the carbon had been like the lead which I showed you, or the iron which, in burning, produces a solid substance, what would happen? Combustion could not go on. As charcoal burns it becomes a vapour and passes off into the atmosphere, which is the great vehicle, the great carrier for conveying it away to other places. Then what becomes of it? Wonderful is it to find that the change produced by respiration, which seems so injurious to us (for we cannot breathe air twice over), is the very life and support of plants and vegetables that grow upon the surface of the earth. It is the same also under the surface, in the great bodies of water; for fishes and other animals respire upon the same principle, though not exactly by contact with the open air.

Such fish as I have here [pointing to a globe of gold-fish] respire by the oxygen which is dissolved from the air by the water, and form carbonic acid, and they all move about to produce the one great work of making the animal and vegetable kingdoms subservient to each other. And all the plants growing upon the surface of the earth, like that which I have brought here to serve as an illustration, absorb carbon; these leaves are taking up their carbon from the atmosphere to which we have given it in the form of carbonic acid, and they are growing and prospering. Give them a pure air like ours, and they could not live in it; give them carbon with other matters, and they live and rejoice. This piece of wood gets all its carbon, as the trees and plants get theirs, from the atmosphere, which, as we have seen, carries away what is bad for us and at the same time good for them,—what is disease to the one being health to the other. So are we made dependent not merely upon our fellow-creatures, but upon our fellow-existers, all Nature being tied together by the laws that make one part conduce to the good of another.

There is another little point which I must mention before we draw to a close—a point which concerns the whole of these operations, and most curious and beautiful it is to see it clustering upon and associated with the bodies that concern us—oxygen, hydrogen, and carbon, in different states of their existence. I showed you just now some powdered lead, which I set burning; and you saw that the moment the fuel was brought to the air it acted, even before it got out of the bottle,—the moment the air crept in it acted. Now, there is a case of chemical affinity by which all our operations proceed. When we breathe, the same operation is going on within us. When we burn a candle, the attraction of the different parts one to the other is going on. Here it *is* going on in this case of the lead, and it is a beautiful instance of chemical affinity. If the products of combustion rose off from the surface, the lead would take fire, and go on burning to the end; but you remember that I have this difference between charcoal

and lead— that, while the lead can start into action at once if there be access of air to it, the carbon will remain days, weeks, months, or years. The manuscripts of Herculaneum were written with carbonaceous ink, and there they have been for 1800 years or more, not having been at all changed by the atmosphere, though coming in contact with it under various circumstances. Now, what is the circumstance which makes the lead and carbon differ in this respect? It is a striking thing to see that the matter which is appointed to serve the purpose of fuel *waits* in its action; it does not start off burning, like the lead and many other things that I could show you, but which I have not encumbered the table with; but it waits for action. This waiting is a curious and wonderful thing. Candles— those Japanese candles, for instance— I do not start into action at once like the lead or iron (for iron finely divided does the same thing as lead), but there they wait for years, perhaps for ages, without undergoing any alteration. I have here a supply of coal-gas. The jet is giving forth the gas, but you see it does not take fire—it comes out into the air, but it waits till it is hot enough before it burns. If I make it hot enough, it takes fire. If I blow it out, the gas that is issuing forth waits till the light is applied to it again. It is curious to see how different substances wait—how some will wait till the temperature is raised a little, and others till it is raised a good deal. I have here a little gunpowder and some gun-cotton; even these things differ in the conditions under which they will burn. The gunpowder is composed of carbon and other substances, making it highly combustible; and the gun-cotton is another combustible preparation. They are both waiting, but they will start into activity at different degrees of heat, or under different conditions. By applying a heated wire to them, we shall see which will start first [touching the gun-cotton with the hot iron]. You see the gun-cotton has gone off, but not even the hottest part of the wire is now hot enough to fire the gunpowder. How beautifully that shows you the difference in the degree in which bodies act in this way! In the one case the substance will wait any time until the associated bodies are made active by heat; but, in the other, as in the process of respiration, it waits no time. In the lungs, as soon as the air enters, it unites with the carbon; even in the lowest temperature which the body can bear short of being frozen, the action begins at once, producing the carbonic acid of respiration; and so all things go on fitly and properly. Thus you see the analogy between respiration and combustion is rendered still more beautiful and striking. Indeed, all I can say to you at the end of these lectures (for we must come to an end at one time or other) is to express a wish that you may, in your generation, be fit to compare to a candle; that you may, like it, shine as lights to those about you; that, in all your actions, you may justify the beauty of the taper by making your deeds honourable and effectual in the discharge of your duty to your fellow-men.

## Marie Skłodowska Curie The Discovery of Radium

*Curie, Eve. Madame Curie: A Biography. Translated by Vincent Sheean. Garden City, NY: Doubleday Doran and Company, Inc., 1937.*

While a young wife kept house, washed her baby daughter and put pans on the fire, in a wretched laboratory at the School of Physics a woman physicist was making the most important discovery of modern science. At the end of 1897 the balance sheet of Marie's activity showed two university degrees, a fellowship and a monograph on the magnetization of tempered steel. No sooner had she recovered from childbirth than she was back again at the laboratory.

The next stage in the logical development of her career was the doctor's degree. Several weeks of indecision came in here. She had to choose a subject of research which would furnish fertile and original material. Like a writer who hesitates and asks himself questions before settling the subject of his next novel, Marie, reviewing the most recent work in physics with Pierre, was in search of a subject for a thesis.

At this critical moment Pierre's advice had an importance which cannot be neglected. With respect to her husband, the young woman regarded herself as an apprentice: he was an older physicist, much more experienced than she. He was even, to put it exactly, her chief, her "boss."

But without a doubt Marie's character, her intimate nature, had a great part in this all-important choice. From childhood the Polish girl had carried the curiosity and daring of an explorer within her. This was the instinct that had driven her to leave Warsaw for Paris and the Sorbonne, and had made her prefer a solitary room in the Latin Quarter to the Dluskis' downy nest. In her walks in the woods she always chose the wild trail or the unfrequented road.

At this moment she was like a traveler musing on a long voyage. Bent over the globe and pointing out, in some far country, a strange name that excites his imagination, the traveler suddenly decides to go there and nowhere else: so Marie, going through the reports of the latest experimental studies, was attracted by the publication of the French scientist Henri Becquerel of the preceding year. She and Pierre already knew this work; she read it over again and studied it with her usual care.

After Roentgen's discovery of X rays, Henri Poincaré conceived the idea of determining whether rays like the X ray were emitted by "fluorescent" bodies under the action of light. Attracted by the same problem, Henri Becquerel examined the salts of a "rare metal," uranium. Instead of finding the phenomenon he had expected, he observed another, altogether different and incomprehensible: he found that uranium salts *spontaneously* emitted, without exposure to light, some rays of unknown nature. A compound of uranium, placed on a photographic plate surrounded by black paper, made an impression on the plate



through the paper. And, like the X ray these astonishing "uranic" salts discharged an electroscope by rendering the surrounding air a conductor.

Henri Becquerel made sure that these surprising properties were not caused by a preliminary exposure to the sun and that they persisted when the uranium compound had been maintained in darkness for several months. For the first time, a physicist had observed the phenomenon to which Marie Curie was later to give the name of *radioactivity*. But the nature of the radiation and its origin remained an enigma.

Becquerel's discovery fascinated the Curies. They asked themselves whence came the energy—tiny, to be sure—which uranium compounds constantly disengaged in the form of radiation. And what was the nature of this radiation? Here was an engrossing subject of research, a doctor's thesis! The subject tempted Marie most because it was a virgin field: Becquerel's work was very recent and so far as she knew nobody in the laboratories of Europe had yet attempted to make a fundamental study of uranium rays. As a point of departure, and as the only bibliography, there existed some communications presented by Henri Becquerel at the Academy of Science during the year 1896. It was a leap into great adventure, into an unknown realm.

There remained the question of where she was to make her experiments—and here the difficulties began. Pierre made several approaches to the director of the School of Physics with practically no results: Marie was given the free use of a little glassed-in studio on the ground floor of the school. It was a kind of store-room, sweating with damp, where unused machines and lumber were put away. Its technical equipment was rudimentary and its comfort nil. Deprived of an adequate electrical installation and of everything that forms material for the beginning of scientific research, she kept her patience, sought and found a means of making her apparatus work in this hole. It was not easy. Instruments of precision have sneaking enemies: humidity, changes of temperature. Incidentally the climate of this little workroom, fatal to the sensitive electrometer, was not much better for Marie's health. But this had no importance. When she was cold, the young woman took her revenge by noting the degrees of temperature in centigrade in her notebook. On February 6, 1898, we find, among the formulas and figures: "Temperature here 6° 25." Six degrees...! Marie, to show her disapproval, added ten little exclamation points.

The candidate for the doctor's degree set her first task to be the measurement of the "power of ionization" of uranium rays—that is to say, their power to render the air a conductor of electricity and so to discharge an electroscope. The excellent method she used, which was to be the key to the success of her experiments, had been invented for the study of other phenomena by two physicists well known to her: Pierre and Jacques Curie. Her technical installation consisted of an "ionization chamber," a Curie electrometer and a piezoelectric quartz. At the end of several weeks the first result appeared: Marie acquired the certainty that the intensity of this surprising radiation was proportional to the

quantity of uranium contained in the samples under examination, and that this radiation, which could be measured with precision, was not affected either by the chemical state or combination of the uranium or by external factors such as lighting or temperature. These observations were perhaps not very sensational to the uninitiated, but they were of passionate interest to the scientist. It often happens in physics that an inexplicable phenomenon can be subjected, after some investigation, to laws already known, and by this very fact loses its interest for the research worker. Thus, in a badly constructed detective story, if we are told in the third chapter that the woman of sinister appearance who might have committed the crime is in reality only an honest little housewife who leads a life without secrets, we feel discouraged and cease to read.

Nothing of the kind happened here. The more Marie penetrated into intimacy with uranium rays, the more they seemed without precedent, essentially unknown. They were like nothing else. Nothing affected them. In spite of their very feeble power, they had an extraordinary individuality. Turning this mystery over and over in her head, and pointing toward the truth, Marie felt and could soon affirm that the incomprehensible radiation was an *atomic* property. She questioned: Even though the phenomenon had only been observed with uranium, nothing proved that uranium was the only chemical element capable of emitting such radiation. Why should not other bodies possess the same power? Perhaps it was only by chance that this radiation had been observed in uranium first, and had remained attached to uranium in the minds of physicists. Now it must be sought for elsewhere.... No sooner said than done. Abandoning the study of uranium, Marie undertook to examine *all known chemical bodies*, either in the pure state or in compounds. And the result was not long in appearing: compounds of another element, thorium, also emitted spontaneous rays like those of uranium and of similar intensity. The physicist had been right: the surprising phenomenon was by no means the property of uranium alone, and it became necessary to give it a distinct name. Mme Curie suggested the name of *radioactivity*. Chemical substances like uranium and thorium, endowed with this particular "radiance," were called *radio elements*.

Radioactivity so fascinated the young scientist that she never tired of examining the most diverse forms of matter, always by the same method. Curiosity, a marvelous feminine curiosity, the first virtue of a scientist, was developed in Marie to the highest degree. Instead of limiting her observation to simple compounds, salts and oxides, she had the desire to assemble samples of minerals from the collection at the School of Physics, and of making them undergo almost at hazard, for her own amusement, a kind of customs inspection which is an electrometer test. Pierre approved, and chose with her the veined fragments, hard or crumbly, oddly shaped, which she wanted to examine.

Marie's idea was simple—simple as the stroke of genius. At the crossroads where Marie now stood, hundreds of research workers might have remained, nonplussed, for months or even years. After examining all known chemical substances,

and discovering—as Marie had done—the radiation of thorium, they would have continued to ask themselves in vain whence came this mysterious radioactivity. Marie, too, questioned and wondered. But her surprise was translated into fruitful acts. She had used up all evident possibilities. Now she turned toward the unplumbed and the unknown. She knew in advance what she would learn from an examination of the minerals, or rather she thought she knew. The specimens which contained neither uranium nor thorium would be revealed as totally "inactive." The others, containing uranium or thorium, would be radioactive.

Experiment confirmed this prevision. Rejecting the inactive minerals, Marie applied herself to the others and measured their radioactivity. Then came a dramatic revelation: the radioactivity was a *great deal stronger* than could have been normally foreseen by the quantity of uranium or thorium contained in the products examined! "It must be an error in experiment," the young woman thought; for doubt is the scientist's first response to an unexpected phenomenon. She started her measurements over again, unmoved, using the same products. She started over again ten times, twenty times. And she was forced to yield to the evidence: the quantities of uranium and of thorium found in these minerals were by no means sufficient to justify the exceptional intensity of the radiation she observed.

Where did this excessive and abnormal radiation come from? Only one explanation was possible: the minerals must contain, in small quantity, a *much more powerfully radioactive substance* than uranium and thorium. But what substance? In her preceding experiments, Marie had already examined *all known chemical elements*. The scientist replied to the question with the sure logic and the magnificent audaciousness of a great mind: The minerals certainly contained a radioactive substance, which was at the same time a chemical element unknown until this day: *a new element*.

A new element! It was a fascinating and alluring hypothesis—but still a hypothesis. For the moment this powerfully radioactive substance existed only in the imagination of Marie and of Pierre. But it did exist there. It existed strongly enough to make the young woman go to see Bronya one day and tell her in a restrained, ardent voice:

"You know, Bronya, the radiation that I couldn't explain comes from a new chemical element. The element is there and I've got to find it. We are sure! The physicists we have spoken to believe we have made an error in experiment and advise us to be careful. But I am convinced that I am not mistaken."

These were unique moments in her unique life. The layman forms a theatrical—and wholly false—idea of the research worker and of his discoveries. "The moment of discovery" does not always exist: the scientist's work is too tenuous, too divided, for the certainty of success to crackle out suddenly in the midst of his laborious toil like a stroke of lightning, dazzling him by its fire. Marie, standing in front of her apparatus, perhaps never experienced the sudden intoxication of triumph. This intoxication was spread over several days of decisive la-

bor, made feverish by a magnificent hope. But it must have been an exultant moment when, convinced by the rigorous reasoning of her brain that she was on the trail of new matter, she confided the secret to her elder sister, her ally always....Without exchanging one affectionate word, the two sisters must have lived again, in a dizzying breath of memory, their years of waiting, their mutual sacrifices, their bleak lives as students, full of hope and faith.

It was barely four years before that Marie had written: "Life is not easy for any of us. But what of that? we must have perseverance and above all confidence in ourselves. We must believe that we are gifted for something, and that this thing, at whatever cost, must be attained". That "something" was to throw science upon a path hitherto unsuspected.

In a first communication to the Academy, presented by Prof. Lippmann and published in the *Proceedings* on April 12, 1898, "Marie Sklodovska Curie" announced the probable presence in pitchblende ores of a new element endowed with powerful radioactivity. This was the first stage of the discovery of radium.

By the force of her own intuition the physicist had shown to herself that the wonderful substance must exist. She decreed its existence. But its incognito still had to be broken. Now she would have to verify hypothesis by experiment, isolate this material and see it. She must be able to announce with certainty: "It is there."

Pierre Curie had followed the rapid progress of his wife's experiments with passionate interest. Without directly taking part in Marie's work, he had frequently helped her by his remarks and advice. In view of the stupefying character of her results, he did not hesitate to abandon his study of crystals for the time being in order to join his efforts to hers in the search for the new substance. Thus, when the immensity of a pressing task suggested and exacted collaboration, a great physicist was at Marie's side—a physicist who was the companion of her life. Three years earlier, love had joined this exceptional man and woman together—love, and perhaps some mysterious foreknowledge, some sublime instinct for the work in common.

The available force was now doubled. Two brains, four hands now sought the unknown element in the damp little workroom in the Rue Lhomond. From this moment onward it is impossible to distinguish each one's part in the work of the Curies. We know that Marie, having chosen to study the radiation of uranium as the subject of her thesis, discovered that other substances were also radioactive. We know that after the examination of minerals she was able to announce the existence of a new chemical element, powerfully radioactive, and that it was the capital importance of this result which decided Pierre Curie to interrupt his very different research in order to try to isolate this element with his wife. At that time—May or June 1898—a collaboration began which was to last for eight years, until it was destroyed by a fatal accident.

We cannot and must not attempt to find out what should be credited to Marie and what to Pierre during these eight years. It would be exactly what the husband and wife did not want. The personal genius of Pierre Curie is known to

us by the original work he had accomplished before this collaboration. His wife's genius appears to us in the first intuition of discovery, the brilliant start; and it was to reappear to us again, solitary, when Marie Curie the widow unflinchingly carried the weight of a new science and conducted it, through research, step by step, to its harmonious expansion. We therefore have formal proof that in the fusion of their two efforts, in this superior alliance of man and woman, the exchange was equal.

Let this certainty suffice for our curiosity and admiration. Let us not attempt to separate these creatures full of love, whose handwriting alternates and combines in the working notebooks covered with formulae, these creatures who were to sign nearly all their scientific publications together. They were to write "We found" and "We observed"; and when they were constrained by fact to distinguish between their parts, they were to employ this moving locution:

Certain minerals containing uranium and thorium (pitchblende, chalcocite, uranite) are very active from the point of view of the emission of Becquerel rays. In a preceding communication, *one of us* showed that their activity was even greater than that of uranium and thorium, and stated the opinion that this effect was due to some other very active substance contained in small quantity in these minerals. (Pierre and Marie Curie: *Proceedings of the Academy of Science*, July 18, 1898.)

Marie and Pierre looked for this "very active" substance in an ore of uranium called pitchblende, which in the crude state had shown itself to be four times more radioactive than the pure oxide of uranium that could be extracted from it. But the composition of this ore had been known for a long time with considerable precision. The new element must therefore be present in very small quantity or it would not have escaped the notice of scientists and their chemical analysis. According to their calculations—"pessimistic" calculations, like those of true physicists, who always take the less attractive of two probabilities—the collaborators thought the ore should contain the new element to a maximum quantity of one per cent. They decided that this was very little. They would have been in consternation if they had known that the radioactive element they were hunting down did not count for more than a millionth part of pitchblende ore.

They began their prospecting patiently, using a method of chemical research invented by themselves; based on radioactivity they separated all the elements in pitchblende by ordinary chemical analysis and then measured the radioactivity of each of the bodies thus obtained. By successive eliminations they saw the "abnormal" radioactivity take refuge in certain parts of the ore. As they went on, the field of investigation was narrowed. It was exactly the technique used by the police when they search the houses of a neighborhood, one by one, to isolate and arrest a malefactor. But there was more than one malefactor here: the radioactivity was concentrated principally in two different chemical fractions of the pitchblende. For M. and Mme Curie it indicated the existence of two new elements instead of one. By July 1898 they were able to announce the

discovery of one of these substances with certainty. "You will have to name it," Pierre said to his young wife, in the same tone as if it were a question of choosing a name for little frene.

The one-time Mile Sklodovska reflected in silence for a moment. Then, her heart turning toward her own country which had been erased from the map of the world, she wondered vaguely if the scientific event would be published in Russia, Germany and Austria—the oppressor countries—and answered timidly: "Could we call it 'polonium'?" In the *Proceedings of the Academy* for July 1898 we read: "We believe the substance we have extracted from pitchblende contains a metal not yet observed, related to bismuth by its analytical properties. If the existence of this new metal is confirmed we propose to call it *polonium*, from the name of the original country of one of us".

The choice of this name proves that in becoming a Frenchwoman and a physicist Marie had not disowned her former enthusiasms. Another thing proves it for us: even before the note "On a New Radioactive Substance Contained in Pitchblende" had appeared in the *Proceedings of the Academy*, Marie had sent the manuscript to her native country, to that Joseph Boguski who directed the little laboratory at the Museum of Industry and Agriculture where she had made her first experiments. The communication was published in Warsaw in a monthly photographic review called *Swiatlo* almost as soon as in Paris.

Life was unchanged in the little flat in the Rue de la Glaciere. Marie and Pierre worked even more than usual; that was all. When the heat of summer came, the young wife found time to buy some baskets of fruit in the markets and, as usual, she cooked and put away preserves for the winter, according to the recipes used in the Curie family. Then she locked the shutters on her windows, which gave on burned leaves; she registered their two bicycles at the Orleans station, and, like thousands of other young women in Paris, went off on holiday with her husband and her child.

This year the couple had rented a peasant's house at Auroux, in Auvergne. Happy to breathe good air after the noxious atmosphere of the Rue Lhomond, the Curies made excursions to Mende, Puy, Clermont, Mont-Dore. They climbed hills, visited grottoes, bathed in rivers. Every day, alone in the country, they spoke of what they called their "new metals," polonium and "the other"—the one that remained to be found. In September they would go back to the damp workroom and the dull minerals; with freshened ardor they would take up their search again.

One grief interfered with Marie's intoxication for work: the Dluskis were on the point of leaving Paris. They had decided to settle in Austrian Poland and to build a sanatorium for tubercular sufferers at Zakopane in the Carpathian Mountains. The day of separation arrived: Marie and Bronya exchanged broken-hearted farewells; Marie was losing her friend and protector, and for the first time she had the feeling of exile.

*Marie to Bronya, December 2, 1898:* "You can't imagine what a hole you have made in my life. With you two, I have lost everything I clung to in Paris

except my husband and child. It seems to me that Paris no longer exists, aside from our lodging and the school where we work. Ask Mme Dluska if the green plant you left behind should be watered, and how many times a day. Does it need a great deal of heat and sun?

We are well, in spite of the bad weather, the rain and the mud. Irene is getting to be a big girl. She is very difficult about her food, and aside from milk tapioca she will eat hardly anything regularly, not even eggs. Write me what would be a suitable menu for persons of her age...." In spite of their prosaic character—or perhaps because of it—some notes written by Mme Curie in that memorable year 1898 seem to us worth quoting. Some are to be found in the margins of a book called *Family Cooking*, with respect to a recipe for gooseberry jelly: "I took eight pounds of fruit and the same weight in crystallized sugar. After an ebullition of ten minutes, I passed the mixture through a rather fine sieve. I obtained fourteen pots of very good jelly, not transparent, which "took" perfectly".

In a school notebook covered with gray linen, in which the young mother had written little Irene's weight day by day, her diet and the appearance of her first teeth, we read under the date of July 20, 1898, some days after the publication of the discovery of polonium: "Irene says "thanks" with her hand. She can walk very well now on all fours. She says "Gogli, gogli, go." She stays in the garden all day at Sceaux on a carpet. She can roll, pick herself up, and sit down".

On August 15, at Auroux: "Irene has cut her seventh tooth, on the lower left. She can stand for half a minute alone. For the past three days we have bathed her in the river. She cries, but today (fourth bath) she stopped crying and played with her hands in the water. She plays with the cat and chases him with war cries. She is not afraid of strangers any more. She sings a great deal. She gets up on the table when she is in her chair".

Three months later, on October 17, Marie noted with pride: "Irene can walk very well, and no longer goes on all fours". On January 5, 1899: "Irene has fifteen teeth!" Between these two notes—that of October 17, 1898, in which Irene no longer goes on all fours, and that of January 5 in which Irene has fifteen teeth—and a few months after the note on the gooseberry preserve, we find another note worthy of remark.

It was drawn up by Marie and Pierre Curie and a collaborator called G. Bemont. Intended for the Academy of Science, and published in the *Proceedings* of the session of December 26, 1898, it announced the existence of a second new chemical element in pitchblende. Some lines of this communication read as follows: *The various reasons we have just enumerated lead us to believe that the new radioactive substance contains a new element to which we propose to give the name of RADIUM. The new radioactive substance certainly contains a very strong proportion of barium; in spite of that its radioactivity is considerable. The radioactivity of radium therefore must be enormous.*

## PART III

### GLOSSARY

**Aberration** in optics, a distortion of the image formed by a lens or mirror, either because of its curvature, or because of differences in wavelength of the light transmitted. From the nineteenth century, both these types, *spherical* and *chromatic*, have largely been corrected in optical instruments.

**Absolute zero** at this temperature, 0°K (kelvin), the lowest theoretically attainable, atoms and molecules are at zero-point energy (making the gaseous state impossible). This is the basis for the standard temperature scale in which 0°C is equivalent to 273.15°K.

**Academic des Sciences** in France, the official institution for protecting and advancing the interests of science. Its members are all elected for their exceptional scientific achievements.

**Air** the basic constituent of the earth's atmosphere, known, since the end of the eighteenth century, to consist mainly of oxygen and nitrogen.

**Atomic nucleus** the positively charged central core of the atom, consisting of protons and neutrons, discovered by Ernest Rutherford (1871-1937) in 1911.

**Atomic number** the number of protons in the *atomic nucleus*, which defines every separate element in the *periodic table*.

**Atomic pile** a large aggregate of *radioactive* elements, embedded in a moderator, designed so as to sustain a continued nuclear *reaction* - as in a nuclear power station.

**Atomic weight** commonly known as 'relative atomic mass', because it relates the mass per atom of the naturally occurring form of an element to 1/12 that of a carbon-12 atom (taken as the standard of measurement).

**Avogadro's hypothesis** at the same temperature and pressure, equal volumes of all gases contain an equal number of molecules.

**Base metals** common metals, such as lead and iron, which deteriorate on exposure to air, moisture and heat.

**Benzene** the archetypical aromatic compound, C<sub>6</sub>H<sub>6</sub>, whose molecule has a ring structure, fundamental in organic chemistry.

**Big bang** an explanation of the origin of the universe, at a finite moment in the past, as a result of the explosion of a state of matter of enormous density and temperature.

**Black-body radiation** electromagnetic radiation emitted by a black body, defined by the property that it absorbs and emits almost all the radiation falling on it. Although a perfect black body can only exist as a theoretical concept, the phenomenon, first observed at the end of the nineteenth century, was critical for



the formulation of *quantum physics* by Max Planck (1858-1947) and others in the early twentieth century.

**Bonding** in chemistry the strong attractive force, taking a number of different forms, which holds atoms together in a molecule or crystal.

**Bose-Einstein condensate** the ultimate state of matter at extremely low temperatures (around  $2 \times 10^{-7}$  °K), at which stage thousands of atoms of a single element become a single superatom, with remarkable physical properties.

**Boyle's law** a particular case of the *gas laws*, governing the relation between mass and volume at a constant temperature.

**Bubble chamber** based on liquid, typically hydrogen, maintained by pressure slightly above its boiling point. Ionisation radiation can then be observed, because the passage of ionised particles reduces the pressure, leading to the formation of a trail of bubbles.

**Caesium atomic clock** whose extreme accuracy, based upon the frequency equivalent to the energy difference between two states of the caesium-133 atom, now defines the second in SI units.

**Carbon** the defining element of all organic compounds, and as such fundamental to life.

**Carbon dioxide** a colourless, odourless gas, CO<sub>2</sub>, present in the earth's atmosphere, and the essential source of carbon for plants, which absorb it by photosynthesis; the supply is continuously replenished by respiration by living organisms, and combustion of fossil fuels, the latter now being responsible for the greenhouse effect.

**Cathode rays** streams of electrons emitted from the *cathode* within a vacuum chamber containing both a cathode and an *anode* - a phenomenon providing the experimental basis of much of modern physics.

**Ceramics** originally produced by the baking of clay, together with other inorganic material, in an irreversible process leading to chemically unreactive end products of extreme stability and a wide range of uses.

**Chain reaction** defined by a series of steps, in which each is the result of the one preceding it, sometimes with a multiplier effect leading to a chemical or nuclear explosion.

**Cherenkov radiation** a phenomenon, characterised by the emission of blue light from a transparent medium, such as water, as a result of passage of atomic particles at a velocity greater than that of light in that medium.

**Cloud chamber** used in the classic early days of particle physics, contains supersaturated vapour, which, by condensing in drops on ions, allows the passage of ionising radiation to be observed.

**Combustion** a chemical reaction between oxygen and some other substance producing heat and light.

**Complementarity** the use of two different but complementary concepts (e.g. particles vs. waves) to explain *quantum* phenomena.

**Compton effect** the loss of energy of X- or y-ray *photons* when they are scattered by free *electrons*.

**Conservation** the principle that the magnitude of a physical property of a system, such as energy, mass or charge, remains unchanged while its distribution within the system is altered.

**Crab nebula** a glowing cloud of gas and dust in the constellation Taurus, a remnant of a *supernova* explosion observed in China in the year 1054.

**Cryometer** any instrument for measuring extremely low temperatures.

**Crystal** a solid having a regular internal arrangement, based on polyhedra, of atoms, ions or molecules.

**Cyclotron** an *accelerator* in which charged particles, introduced at the centre, are accelerated along an outward spiral path.

**Dalton's atomic theory** first proposed a standard atom, which could neither be created nor destroyed, as the fundamental unit defining any element.

**Domestication** the historical process by which humankind has come to control the number, distribution and selective development of specific plants and animals, primarily for consumption as food.

**Doppler effect** the observed change in the frequency of a wave as a result of the motion of its source in relation to the observer.

**Electric arc** historically the first means of using an electric current for lighting, is essentially an incandescent discharge caused by the current between two *electrodes*, in which the *ionisation* of the gap separating them maintains a conductive medium allowing the effect to continue indefinitely.

**Electrode** a conductor that emits (*anode*) or collects (*cathode*) electrons in a cell, vacuum tube, semiconductor, etc.

**Electrolysis** the process by which the passage of an electric current through a conducting liquid (the electrolyte), causes the concentration of positive ions at the *anode*, and negative ions at the *cathode*.

**Electromagnetism** the fundamental phenomenon inherent in the relation between electricity and magnetism.

**Electron** the elementary negatively charged particle, present in all atoms, grouped in electron shells surrounding the nucleus.

**Electron microscope** using a beam of *electrons* instead of a beam of light, produces much larger images of the object observed than the classic optical *microscope* (whose resolution is limited by the comparatively long wavelengths of the visible *spectrum*).

**Element** in chemistry a substance that, because it cannot decompose into simpler substances, is defined by a single atom.

**Elementary particles** the fundamental constituents of all matter throughout the universe - whose presence (to be distinguished from that of atoms) was first revealed by the discovery of the *electron* in 1897.

**Euratom** the European Atomic Energy Commission, belonging to the European Union and devoted to promoting the peaceful use of atomic energy.

**Femtochemistry** the study of chemical *reactions*, typically the breaking and formation of individual chemical bonds in compounds, which occur within a timespan measured in femtoseconds ( $10^{-15}$  seconds).

**Fermi-Dirac statistics** describes a system of particles obeying the rules of *quantum* rather than classical mechanics, in which only one particle can occupy a given quantum state. Such particles are known as *fermions*, in contrast to *bosons*, governed by *Bose-Einstein* statistics.

**Fire** a continuous form of *combustion* producing, typically, both heat and light.

**Fraunhofer lines** dark lines in the *spectrum* of sunlight caused by the absorption, by elements in the sun's outer surface, of corresponding wavelengths of the radiation emitted from its interior. Their discovery was critical to the development of *spectroscopy*.

**Fundamental interactions** the four basic interactions between separate bodies - gravitational, electromagnetic, strong and weak - which together account for all forces observed to occur in the universe.

**Gas laws** govern the relation between temperature, pressure and volume in ideal gases.

**Geiger counter** devised in 1908 as one of the earliest means of detecting and measuring *ionising* radiation.

**Gluon** a chargeless particle, with no rest mass, visualised as being exchanged between *quarks*, in maintaining the strong interaction between them.

**Gravity** the particular case of the gravitational force (the weakest of the four *fundamental interactions*) operating on any object with mass within the earth's gravitational field.

**Hadron** the class of subatomic particles (including *protons* and *neutrons*) related to the strong interaction (and believed to consist of *quarks*).

**Half-life** the time taken for *radioactive* decay to transform half the radioactive particles present in any aggregate.

**Hall effect** the production, by a current flowing through a strong transverse magnetic field, of a difference in electric potential at right angles to both current and the field.

**Heisenberg's uncertainty principle** discovered in 1927, according to which there is a quantum limit,  $h/4\pi$ , to the accuracy to which both the position and the momentum of an elementary particle can be determined.

**Helium** a colourless, inert gas, with no known compounds and the lowest boiling point of all elements.

**Hippocratic oath** the fundamental ethical code governing the behaviour of doctors since ancient times.

**Homo sapiens sapiens** the last stage in the evolution of humankind, occurring some 100-120 thousand years ago, and characterised by the use of language.

**Hydrocarbon** any one of a vast range of chemical compounds containing only *hydrogen* and *carbon*.

**Hydrogen** the first and lightest element in the *periodic table*, and the only one with no neutrons in the nucleus of its most common *isotope*, is a highly reactive, colourless, odourless gas, present in water and all organic compounds

**Incandescence** light emitted as a result of raising any substance (such as a lamp filament) to a sufficiently high temperature.

**Induction** in physics, the change in the state of a body as the result of its being placed in a field, typically *electromagnetic*.

**Inertia** the inherent property of matter causing it to resist any change in its motion.

**Interference** the interaction of wave motions so as to produce a resultant wave whose form characterises the original waves; in optics, a phenomenon strongly supporting the wave theory of light.

**Isotope** defines an atom of a given element according to the number of *neutrons* in the nucleus, so allowing any element to have a number of different isotopes (some with special properties, such as *radioactivity*).

**Josephson junction** a device applying the electrical properties of matter at the ultra-low temperatures to measuring electric currents at the level of single electron pairs.

**Lepton** any one of a class of elementary particles, including *electrons* and *neutrinos*, subject to both the electromagnetic and the *weak fundamental interactions*.

**Light** scientifically defined by the range of electromagnetic frequencies (the visible spectrum) to which the eye is sensitive.

**Metrology** the science of measurement, in particular for scientific purposes requiring extreme accuracy.

**Microorganisms** a wide heterogeneous class, including bacteria, protozoa, etc., that can only be observed with the help of a microscope (whose invention in the seventeenth century led to the first discovery).

**Microscope** any device for obtaining a magnified image, beyond the range of normal vision, of small objects.

**Molecule** the basic unit in chemistry, typically comprising separate elements, defined as the smallest part of a compound that can take part in a chemical reaction.

**Natural philosophy** until well into the nineteenth century, the generic term for all the exact sciences, except for optics and pure mathematics.

**Neutron** the fundamental uncharged particle comprising the atomic nucleus, but in isolation subject to  $\beta$ -decay into a proton and an electron.

**Nitrogen** a colourless gaseous element, constituting some three-quarters of the earth's atmosphere, and now known to be an essential constituent of proteins and nucleic acids in living organisms.

**Noble gases** the gaseous elements helium, neon, argon, krypton, xenon and radon, belonging to group 18 in the *periodic table*, all representing the termination of a period by closing the electron shell. The result is a capacity to form compounds so restricted that the first instances were only discovered in 1962.

**Notation** the use of special signs, or the idiosyncratic use of common signs, such as letters in chemical compounds, to designate entities with a special significance within the related branch of science.

**Nucleus** the positively charged central core of the atom, consisting of *protons* and (except for *hydrogen*) *neutrons* bound together by the *strong interaction*.

**Oxidation** originally a chemical reaction with oxygen, as opposed to one involving the loss of oxygen, or reduction. Now it defines a number, positive or negative, defined by the number of electrons over which an element has gained or lost control, as a result of it forming part of a compound. Since the process involves the transfer of electrons between the outer shells, it occurs only in *reactions* involving *ions* - which are, however, extremely common.

**Oxygen** a colourless, odourless, gaseous element, making up nearly half the earth's crust, and more than a quarter of its atmosphere, indispensable for all living organisms which acquire their energy by oxidizing nutrients to *carbon dioxide* and water.

**Periodic table** since about 1870, systematically arranges the elements, in rows and columns, according to the unit increase in *atomic number*, taking into account common properties (such as degree of reactivity) to determine the division into rows and columns.

**Phlogiston** a hypothetical substance which, during the seventeenth and eighteenth centuries, was believed to be contained in all combustible substances, to be released in the process of combustion.

**Phosphorus** a common, highly reactive, combustible element, discovered in the seventeenth century, and essential for the support of life.

**Photon** (from the Greek *phos*, 'light') the *quantum* of *electromagnetic* radiation, travelling at the speed of light with a rest mass of zero, and essential for explaining *inter alia* the photoelectric effect and non-wave phenomena.

**Pile** a structure created by the aggregation of separate reacting elements, to increase the energy supplied, as with the electric current coming from the *voltaic pile*.

**Plasma** in high-energy physics, the state of matter, generally at extremely high temperatures, characterised by a high level of *ionisation*, abundant *free electrons*, leading to near impossibility of forming chemical bonds. The greater part of the material universe consists of plasma.

**Polarisation** confines the vibrations of a transverse wave to one direction. In optics, the phenomenon occurring in a number of different ways - in which light waves are only transmitted in one plane.

**Proton** the particle within every atomic *nucleus* which accounts for its positive charge.

**Proton-proton reaction** the means by which energy is generated by nuclear fusion reactions, involving *hydrogen* and *helium*, within main sequence stars with mass comparable to or less than that of the sun.

**Positron** the elementary positively charged particle corresponding to the negatively charged *electron*, but only detected in the 1930s.

**Proper motion** the apparent motion of stars across the sky in relation to the whole firmament, best observed with powerful telescopes over long periods of time, and explained mainly by the closeness of any star observed to the observer.

**Pyrometer** any instrument for measuring extremely high temperatures.

**Radical** in chemistry the stable part of a substance that retains its identity through a series of *reactions* even though a compound.

**Radioactivity** the spontaneous disintegration of certain 'radioactive' atomic nuclei by the emission of *and*  $\alpha$ - or  $\beta$ -particles, or  $\gamma$ -radiation.

**Reaction** in chemistry, a change, spontaneous or deliberate, in one or more elements or compounds such that a new compound is produced.

**Reactive series** an ordered list of generally metallic elements based on their propensity to react with other substances, and indicating therefore their relative stability.

**Reflection** the return of all or part of a beam of particles or waves (typically of light) as a result of encountering the interface between two media.

**Refraction** the change in direction of a beam of particles or waves (typically of light) as it passes from one medium into another. Where the latter is a crystal, the beam may split into two components, each with distinctive optical properties such as *polarisation*: this is double refraction.

**Royal Institution** a learned scientific society, founded in London in 1799, whose laboratories became Britain's first research centre.

**Royal Society** a scientific institution, in continuous existence since its foundation in 1660, whose members, known as 'Fellows', are elected on the basis of their original contribution to the advancement of science.

**Semiconductor** a crystalline solid, with conductivity substantially higher than that of an insulator and lower than that of a conductor, and electrical properties that ensure that according to input the flow of current is either enhanced or inhibited - a property extremely useful in computers and amplification systems.

**SI units** (Système International d'Unités), with the metric system as starting point, internationally recognised for all scientific purposes, and consisting of seven base units and two supplementary, with eighteen more derived from them.

**Silicon** the second most abundant element in the earth's crust, typically a component of sand and derivatively, glass, but now used extensively as the basis for *semiconductors*.

**Thermodynamics** the general study of the transfer of heat linked to the conversion of energy and its availability to do work; see also the *mechanical equivalent of heat*.

**Transition elements** the three main series, belonging to the *d*-block in columns 4 to 12 in the *periodic table*, are typical metals, whose chemical properties are defined by unfilled *d*-orbitals, but this does not define the whole class, which extends also to the *f*-block.

**Valency** the combining power of an atom to form molecules, generally compound, expressed as a whole number according to the number of bonds capable of being formed by outer shell *electrons*.

**X-ray crystallography** a standard technique - particularly useful in the life sciences - using *X-ray diffraction*, for determining the microstructure of crystals or molecules.

## APPENDIX

With the following key words and phrases you will be able to comment on scientific articles or any other pieces of information:

1. The present article/ report is about/is concerned with/ is devoted to ...
2. This essay/ paper deals with/ centres on/ concentrates on/ touches upon/ focuses on/ presents ...
3. The main concern of this paper will be on ...
4. The paper presents the analysis ...
5. The discussion will be concentrated on ...
6. I shall confine my attention strictly to ..
7. We shall concern ourselves with the problem of ...
8. I shall dwell upon the problem of ...
9. Here we need to consider the problem of ...
10. We are facing the problem ...
11. The current interest in the problem lies in ...
12. The problem arises in connection with...
13. We turn our attention to a new and more urgent problem.
14. We shall examine the relations between ...
15. It would be instructive to examine in detail ... from the point of view of
16. There is no mention about ...
17. The report should introduce you to the ideas and directions of ...
18. We shall make a thorough study of ...
19. In this connection it worth while mentioning ...
20. The study of ... raises several interesting problems of a general nature.
21. It requires a detailed study of ...
22. ... got me interested.
23. This is achieved by comprehensive study of ...
24. In connection with the study of various phenomena it is necessary to ...
25. The present book is aimed at ...
26. One of the chief aims was to test the hypothesis...
27. The purpose of my work is to examine and investigate ...
28. We are fully aware of the nature of the objective ...
29. This paper is aimed to reveal some of the features of ...
30. This paper abounds in illustrative material/examples.
31. He was the first to state clearly the concept of ...
32. The essence of the conception is ...
33. The key-note of the article ...
34. To have a good/ bad/ high/ low opinion of smth
35. To state one's views on smth
36. From my point of view
37. To have a position on smth

38. To have an outlook on smth
39. To form a judgment
40. In my judgment
41. To look at smth from the standpoint of ...
42. To take a stand on smth
43. To have a thinking on the matter
44. To take/ to have an attitude to ...
45. To regard/ to guess/ to conjecture/ to surmise/ to grant/ to presume/ to assume/ to suppose/ to figure / to reckon/ to believe/ to stand/ to consider/ to look on/ upon smth
46. To present a workable solution to smth
47. The main (specific) points/ basic concepts/ major problems/ general questions
48. Then, further (on) / the article goes on to say that ...
49. To show and prove the existence and seriousness of a problem
50. To illustrate several phenomena in the field of (Psychology, Physics, Maths, Mechanics, Computing)
51. The text contains the definition of such a phenomenon as (this phenomenon is defined as follows: ...)
52. Clarity and persuasiveness of the ideas
53. Theory and practice/ experimental data/ established facts
54. To assess (to give a critical assessment of the fact)
55. It's my belief/ conviction/ persuasion that...
56. The reporter/ commentator/ author mentions/ reports on/ comments on/ touches upon/ dwells upon/ explains/ gives a detailed analysis of/ describes in detail/ gives no details as to/ gives full coverage of/ reminds the reader of/ focuses the reader's attention on/ emphasizes the fact that/ lays the emphasis on/ stresses that/ draws the reader's attention to/ takes a critical view of / is in favour of ...
57. It is an urgent/ vital/ burning/ bread-and-butter problem.
58. I arrive at a conclusion that ...
59. In conclusion the article says that...
60. At the end of the article the reporter ...
61. To sum up ...
62. The commentator concludes by saying that...
63. That brings me to the end of my commentary.
64. That seems to be all I wanted to tell you.



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