CHEMISTRY, MATTER AND LIFE

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PREFACE

When one considers the vast number of people who know a great deal about the working and construction of that very complicated piece of scientific apparatus, the motor car, there seems no reason why a great deal of modern science should not be equally familiar to the general public. We have endeavoured in this book to take a step in that direction. We have tried to describe in language that any educated person can understand some of the main principles of chemistry, the nature of matter, and some of the chemical changes that take place in living plants and animals. Some of the chapters, we think, will be read with ease; others deal with complicated conditions that of necessity require rather close attention on the part of the reader.

We have been greatly assisted by the advice of many friends who have read the MS. and helped us to make the book more accurate and easier to read. We thank all these most gratefully, and in particular we thank the publishers, whose patience and care have been exceptional. Without their advice the book would not be so good as it is; they have made valuable suggestions for its improvement and taken immense trouble over it.

Stephen Miall.

L. M. Miall.

May 1937.

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CHAPTER I

SOME EARLY PIONEERS

We are trying in this book to explain in the simplest possible language the nature of material things, the changes they undergo as the result of chemical action or the influence of light, the nature of the substances that exist in living plants and animals, and how these alter in the ordinary course of their lives. The corrosion of metals, the nature of alloys, the structure of crystals, the building up of chemical compounds, digestion, respiration, fermentation, and combustion are examples of the topics we shall discuss. Many of these could not have been described simply and accurately thirty years ago, but our knowledge has increased so rapidly during this century that the task we have set ourselves seems now to be possible of achievement.

Modern work on the structure of the atom, on vitamins, on insulin, on drugs, *X*-rays, and electricity, has thrown light on many questions that were formerly obscure, and the story is a fascinating one, although it is not easy to explain the results of chemical research to those whose knowledge of chemical terms is limited. There is an obvious reason for this difficulty. Many of the familiar materials with which we are so well acquainted—wood, paper, bone, meat, and coal—are very complicated substances: so complicated that a hundred or fifty years ago it seemed that it was almost hopeless to understand how they were built up. The early chemists spent much of their time in studying not the familiar complicated substances, but the simpler, if rarer, ones; they investigated the elements, gold, silver, iron, lead, tin, carbon, sulphur, phosphorus, and others that had been known for a very long time. They found that the air is a mixture of oxygen and nitrogen, that water is a compound of oxygen and hydrogen; they discovered the yellowish gas, chlorine, an element that is contained in common salt. With these elements, and twenty or thirty others less familiar to most of us, they performed all kinds of experiments that have very greatly enlarged our knowledge; but most of the substances made by them are unknown outside chemical laboratories or chemical books. Their very names are unfamiliar and repellent; many of these names are long, and are meaningless except to those who possess the clues and know the chemists' language.

Fortunately, it is not necessary for our purpose to make use of many of these terms; we are dealing more with principles than with details, and to illustrate these principles we propose, so far as possible, to avoid instances that cannot be explained in a simple manner. From carbon and hydrogen, chemists have been able to prepare hundreds of different compounds; benzene, or benzol as motorists call it, is one of the few which are familiar friends, though many compounds of carbon and hydrogen are contained in such mixtures as petroleum and petrol. From carbon, and hydrogen, and oxygen hundreds of other compounds have been made, most of which are equally unfamiliar to us. They are of importance because they have helped us to learn the constitution and nature of alcohol, cane-sugar, cellulose, artificial silk, cotton, starch, and a whole host of well-known substances. Of the many thousands of comparatively simple substances made by chemists in their laboratories, a few score have been of the utmost value in understanding the nature of chemical change and the processes that occur in living organisms.

It is convenient, because many of the simpler compounds were investigated first, to take a few instances from the early days, when chemistry began to be a science, so as to lead us on to a consideration of the more complicated structures and the singular processes that cannot easily be explained until we have grasped some of the most fundamental articles in the chemist's creed.

About a hundred and fifty years ago it was recognized that chemical elements existed, and that by the combination of these a multitude of compounds could be formed. The elements copper, silver, gold, sulphur, carbon, mercury, tin, lead, iron, arsenic, antimony, and phosphorus had long been known. Platinum, zinc, cobalt, and nickel were fairly recent discoveries; during the last half of the eighteenth century the gases hydrogen, oxygen, chlorine, and nitrogen were prepared and recognized as elements, and a very few years later attempts were made to prepare other elements which had not been isolated, although compounds of them were known. Among these elements we may mention silicon, boron, aluminium, calcium, sodium, potassium, and magnesium.

These were the elementary substances available for the use of chemists a hundred and fifty years ago. Chemical experiments were then carried out in a room that more resembled an old-fashioned kitchen than a modern laboratory (see Frontispiece, Plate I); most of the chemical appliances were very crude; coal-gas was not available, and the electric current did not come into use until after Volta's discovery of a primitive electric cell in 1791. There was no systematic teaching of chemistry, and the early workers had to make a good deal of their primitive apparatus; petrol and paraffin were unknown, and there were very few chemicals that you could buy at a shop, although drugs had, of course, been readily purchased for many years.

The first stage in the science of chemistry was to recognize the distinction between elements and compounds. The next stage was to recognize that one element could only combine with another in certain definite proportions. Thus hydrogen combines with oxygen, in the proportion of one part of hydrogen by weight and eight parts of oxygen, to form water, and in the proportion of one part of hydrogen by weight and sixteen parts of oxygen to form hydrogen peroxide. It will be seen that the difference in the relative weights of hydrogen and oxygen can cause great differences in the properties of the compound. It is the extra atom of oxygen that gives hydrogen peroxide its bleaching and disinfecting properties. When charcoal or coke burns in an open grate, twelve parts by weight of carbon combine with thirty-two parts by weight of oxygen to form carbon dioxide. The exhaust gases from a motor-car frequently contain a certain quantity of the poisonous carbon monoxide, in which twelve parts by weight of carbon are combined with sixteen parts of oxygen. These two are the only compounds of carbon with oxygen that have been ever prepared in a large quantity, though unusual compounds in which carbon and oxygen are combined in different proportions have been prepared in very minute quantities; in general, one element will only combine with another in one, two, or three proportions comparable with those we have already mentioned in the case of hydrogen and oxygen, and carbon and oxygen.

One of the early workers who helped to establish the science was Cavendish. Henry Cavendish was born in 1731, the elder son of Lord Charles Cavendish, and grandson of the Duke of Devonshire; he was educated at Cambridge, and until he was about forty he lived on a very moderate allowance from his father and contracted very economical habits. He lived at Clapham Common and had a library in Soho, and his methodical nature was such that he never took a volume from his own shelves without entering it in a book. He became a Fellow of the Royal Society in 1760, and dined regularly with the club that was formed from the fellows; otherwise he shunned society and was painfully shy when strangers were introduced to him; he ordered his dinner by a note placed on his table, and his women servants were instructed to keep out of his sight; his dress was old-fashioned and often shabby, for his whole interest was in science; he hated to be bothered about business matters, and on one occasion his bankers found that he had something like £80,000 in their hands, and they sent a representative to see Mr. Cavendish; the following conversation ensued:

"We have a very large balance in hand of yours, and wish for your orders respecting it."

"If it is any trouble to you, I will take it out of your hands. Do not come here to plague me."

"Not the least trouble to us, sir, not the least; but we thought you might like some of it to be invested."

"Do so, and don't come here and trouble me, or I will remove it."

Occasionally he invited a few friends to dine at his house, and invariably gave them a leg of mutton; once he asked four scientific men to dine with him, and when the housekeeper asked what should be got for dinner Cavendish replied:

"A leg of mutton."

"Sir, that will not be enough for five."

"Well, then, get two."

This anecdote illustrates not merely the oddity of the man, but also the small size of the leg of mutton in those days. Since the enclosure of pastures and the use of fertilizers the size of sheep and cattle has increased very much. One leg of mutton would now be ample for a larger party of scientific men.

Cavendish was one of the very great men of science; he was remarkably exact and painstaking, and his experiments were of great importance. He prepared hydrogen and studied its density and its power of combining with oxygen so as to form water, and was the first man to have a clear idea of the composition of water. He determined with great exactness the composition of the air, proving that it was a mixture of about one part of oxygen with four parts of nitrogen, and that, in addition to these gases, the air contained about 1 per cent. of a different gas; he collected a little of this and recorded the experiment carefully; he did not know what it was, but a hundred years later Rayleigh and Ramsay discovered the gas argon, that is now often used to fill electric-light bulbs, and they found that the gas that had been collected by Cavendish was argon. Cavendish also studied the production of oxides of nitrogen—compounds of oxygen and nitrogen—produced by means of electric sparks in a mixture of oxygen and nitrogen, and he worked at the composition of nitric acid. Nitric acid is a compound of nitrogen, oxygen, and hydrogen; it is a very useful liquid in chemical research and of great commercial importance, playing a part in the manufacture of explosives and fertilizers. In these ways Cavendish laid an exact foundation for the study of some of the most important elementary gases. He studied heat and electricity, and determined the density of the earth, and busied himself with geology; but these researches are rather outside our subject. He died in 1810, leaving a fortune of a million pounds and having enriched chemistry by two researches of great value, the composition of air and the composition of water (see Plate II).

His contemporary Joseph Priestley was as unlike Cavendish as it would be possible to be; he was born in 1733 of parents in humble circumstances, and at the age of seven was taken charge of by an aunt and educated to become a nonconformist minister. In his young days he studied electricity, and wrote a history of it which secured his election to the Royal Society in 1766. He became a Unitarian minister in Leeds, and was attracted to the study of chemistry, partly because he lived next door to a brewery where quantities of carbon dioxide were produced in the ordinary course of the fermentation of beer. He became librarian to Lord Shelburne in 1772, and remained with him for seven years investigating the different kinds of gases and making important discoveries. He was the first to prepare and publish an account of sulphur dioxide, ammonia gas, nitrous oxide (laughing gas), and oxygen. The last gas he discovered in 1774, not knowing that two years or so earlier the Swedish chemist Scheele had also discovered it, but had not published his discovery. Priestley proved that green plants are able in sunlight to absorb carbon dioxide from the air and make use of it, and to restore to the air a certain quantity of oxygen. He played a part in the discovery of the composition of the air, and invented soda-water, which has nothing to do with soda, but is merely water in which a considerable quantity of carbonic acid (carbon dioxide) has been dissolved. Priestley at one time learned many foreign languages and taught them; he was a vehement theologian and a keen politician, with radical or revolutionary views; he was acrimonious in his writings, and made himself very unpopular in Birmingham, where he went to live in 1780. During the riots of 1791 the mob wrecked his house and burned his books, and he was in some danger of losing his life. Finally he emigrated to America, and died there in the year 1804.

Carl Wilhelm Scheele was another early pioneer; he was born in 1742 at Stralsund in Pomerania; when he was fourteen he was apprenticed to an apothecary at Goteborg in Sweden, and then began to experiment in chemistry. He became an apothecary at Malmö, then at Stockholm, Upsala, and Köping in Sweden, and spent all his spare time in his chemical studies. He independently discovered oxygen, ammonia, and hydrochloric acid gas (a compound of hydrogen and chlorine); he was the first to isolate the gas chlorine and to discover hydrofluoric acid, a compound of hydrogen and fluorine used for etching glass; he was also the first to prepare lactic acid, oxalic acid, citric acid, and tartaric acid; lactic acid occurs in sour milk, oxalic acid in the sorrel herb, citric acid in lemon juice, tartaric acid is made from grape juice. He was the first to isolate glycerine, and the sugar contained in milk, now called lactose, an important component of some infant foods; he prepared prussic acid (hydrocyanic acid, a compound of hydrogen, carbon, and nitrogen), and he found out the nature of prussian blue, and made many other discoveries of great interest. Cavendish, Priestley, and Scheele made so many discoveries of new elements and new compounds, and did their work so thoroughly, that chemistry was enriched by a great mass of facts that enabled later workers to deduce from them the laws of chemical combination. Had Scheele lived to be an old man the volume of his discoveries would doubtless have been much greater, but he died in 1786, in his forty-third year.

None of these three men knew much about the theory of chemistry, or the laws of chemical combination, or the nature of chemical compounds, and the little they guessed about these matters was confused and inaccurate. It was a young French chemist, Lavoisier, with that logical kind of mind that is commoner in France than elsewhere, who reduced the chaos to order, distinguished exactly between chemical elements and chemical compounds, gave names to most of the new elements, and devised a logical system of names for the numerous chemical compounds.

Antoine-Laurent Lavoisier was born in Paris in 1743, and studied chemistry at the Jardin du Roi; he was the first to show that the "setting" of plaster of Paris is due to the taking up of water by the dry plaster and the combination of the two; he was soon elected a member of the French Academy. In 1768 he became a member of the *Ferme-générale*, a company to which the Government, in return for a fixed sum of money, granted the right of collecting many of the taxes. He was later made a Powder Commissioner, and effected improvements in the manufacture of saltpetre and gunpowder; he drew up reports on the cultivation of flax and potatoes and prepared a scheme for establishing experimental farms; he introduced the cultivation of the beet, and helped to improve the breed of sheep; he was secretary of the Commission of Weights and Measures that devised the metric system, and he rendered great services to his country and to chemistry. But his connexion with the *Ferme-générale* and the Government was his ruin. In 1793 the Convention ordered the arrest of the twenty-eight members of the *Ferme-générale*; they were arrested and sentenced to death; a plea was made on behalf of Lavoisier, but the officer in charge declared: "La république n'a pas besoin des savants." Lavoisier was executed and his property confiscated.

Some of those who experimented in the new pastime, or science, improved the apparatus that was employed in it. Each such improvement enabled new discoveries to be made. That has remained true to some extent ever since; at any rate, it is due to the extraordinary improvements in our scientific instruments that many of our greatest modern discoveries have been made. Modern science depends upon accurate observation far more than ingenious speculation, and our knowledge of matter and its ways would be very imperfect but for our marvellous microscopes, spectroscopes, vacuum pumps, thermostats, and the other triumphs of physics and engineering. Cavendish and his contemporaries had none of these; they would have done far more if they had.

Like so much else in this world, our knowledge of the structure of matter and the nature of chemical change is very largely a case of evolution. Our alphabet is the result of three or four thousand years of gradual experiment and development, the steam-engine the result of effort and improvement spread over a few hundred years. Almost every scientific discovery depends upon observations made by earlier workers. When a sufficient mass of facts has been accumulated some one comes along and finds out a law connecting them. It was necessary to have the careful work of the four great men we have mentioned, and many men of less fame, before an adequate explanation of the facts could be given; as is usual, the explanation was not due to one man alone: several of his predecessors had made guesses with some foundation of truth in them; but until all the necessary data had been collected, the theory could neither be proclaimed nor proved. The man who gave us the first great chemical theory, one that is still universally accepted, was John Dalton, not such a scientific genius as Cavendish or Lavoisier, not such a prolific discoverer as Priestley or Scheele, but a simple-minded, clear-thinking man who tried to interpret the facts simply and clearly, and succeeded in doing so. To Dalton we owe the modern theory of atoms; it was he who first believed that every element was composed of infinitely small atoms each exactly like the other, and that the atoms of any one element were different from the atoms of any other element. He pictured an atom of element *A* combining with one, or perhaps two, or perhaps three, atoms of another element *B*, and that this was the basis of all chemical combination. This is now as obvious to us all as the existence of petrol, but it was not obvious a hundred and thirty years ago. Now when we read Darwin's *Origin of Species* it seems that he devoted several hundred pages to prove what needed only to be stated in one page; his conclusions are obvious to everybody. It is hard for us to put our minds in the state that was characteristic of educated people some seventy or eighty years ago.

John Dalton, the son of a Quaker weaver, was born in Cumberland in 1776, and became a teacher in Manchester and afterwards the Secretary of the Manchester Philosophical Society. He studied meteorology, and experimented on gases, in particular some of the gaseous compounds of carbon and hydrogen, one of which is known as methane or marsh-gas; he was also the first person to call attention to colour-blindness; he himself had this peculiarity to a marked extent. After a life free from excitement, he died in 1844.

Dalton's views did not encounter the opposition that met Darwin's views; the ancient Jewish writers had not speculated on the constitution of matter, and no question of religion or orthodoxy was involved. Dalton's Atomic Theory was published in 1807, and has never since been disputed, though modern research on the structure of the atom has led to some interesting developments. Dalton was able to calculate very roughly the relative weights of many of the various atoms. Water, he knew, consisted of one part by weight of hydrogen and eight parts by weight of oxygen. The chemists of that period did not know whether they ought to regard water as composed of two atoms of hydrogen with a relative weight of 1 each and one atom of oxygen with a relative weight of 16, or whether they ought to regard water as composed of one atom of hydrogen with a relative weight of 1 and one atom of oxygen with a relative weight of 8. Either supposition fitted in with the facts.

The chemists during the next twenty or thirty years did not spend much time in discussing such a supposition; perhaps they thought it was too metaphysical, or at any rate a waste of time, and they busied themselves in discovering new elements and new compounds, in analysing all kinds of minerals and substances of animal or vegetable origin, in studying the shapes of crystals, and in scores of other ways. They improved very greatly their methods of analysis, and Dalton's crude list of the relative combining weights of a few elements was superseded by a far more accurate list of atomic weights—that is, relative atomic weights—of some fifty or sixty elements.

Various scientific men investigated the density of different gases and the effect of compression on them and the way in which a gas expands when it is heated, and after the publication of Dalton's Atomic Theory an Italian physicist named Avogadro published his views on the nature of the ultimate small particles of elementary or compound gases. Translating his notions into modern terms, we may say that he regarded hydrogen as a gas containing a practically infinite number of molecules, each molecule consisting of two atoms of hydrogen; chlorine gas consisted of molecules each of which was made up of two atoms of chlorine. When hydrogen combines with chlorine to form hydrogen chloride (or hydrochloric acid gas), we consider that a molecule of each gas splits up into its two atoms, and that *two new molecules are formed, each containing one atom of* hydrogen and one atom of chlorine. Avogadro stated in 1811 that whatever gas you considered, a cubic foot of it would contain the same number of molecules as a cubic foot of any other gas, assuming that the temperatures and the pressures were the same. This was really a considerable development, but it attracted very little attention among chemists; it was not in advance of the facts, but in advance of the ideas of scientific men.

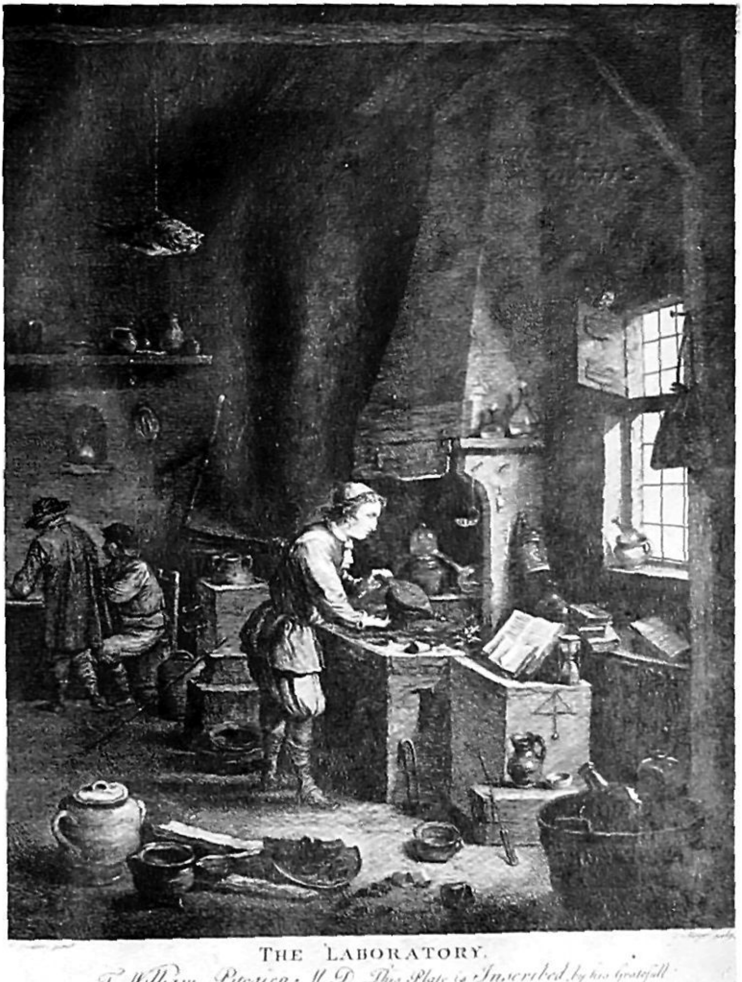
We can mention another and more recent instance of a molecular theory being in advance of its time. We now believe that every gas consists of a number of molecules dashing about at a great speed, and when these hit the side of a vessel containing the gas, they exert a pressure on it. It is possible to calculate the number of molecules in a given volume of any gas, at a fixed temperature and pressure, to calculate the average speed of the molecules, and other such matters. This theory was developed by Waterston in 1845, by Clausius in 1857, and by Clerk Maxwell in 1859. Waterston, who anticipated the views of Clausius and Clerk Maxwell, was several years in advance of scientific opinion, and when his paper was submitted to the Royal Society, the referee said: "The paper is nothing but nonsense, unfit even for reading before the Society." But although Waterston's paper was not published at the time, it was preserved, and in 1892 Lord Rayleigh called attention to its importance, and at last arranged for its publication with a suitable explanation.

A very versatile man of science was William Hyde Wollaston, the son of a clergyman, who had fifteen children who grew up to manhood. After studying at Cambridge, Wollaston became a country doctor, but he soon came to London to devote himself to science. He engaged in the manufacture of platinum, and made a considerable sum of money in this way; he invented an instrument, the reflecting goniometer, to enable the angles of crystals to be measured accurately, and he made slide-rules as ready appliances for making calculations.

In the year 1812 Wollaston discovered that certain compounds of similar metals crystallized in similar crystals having angles very nearly but not quite the same; thus calcium carbonate (calcite), a compound of calcium, carbon, and oxygen, crystallizes in rhombohedra with an angle of 105° 5′, calcium magnesium carbonate (dolomite), a compound of calcium, magnesium, carbon, and oxygen, crystallizes in rhombohedra with an angle of 106° 15′, and iron carbonate (siderite) crystallizes in rhombohedra with an angle of 107° 0′. This phenomenon, called isomorphism, is dealt with in Chapter VI. Wollaston discovered a new silvery-looking element called palladium, but he was an odd man and he made his discovery known in an odd and provoking way. Having prepared a small quantity of this metal, he thought he would play a practical joke on another chemist named Chenevix. He arranged in April 1803 that a printed notice should come into the hands of Chenevix stating that a new metal called palladium was to be sold at Mrs. Forster's of Gerrard Street, Soho. Chenevix, believing that it was a fraud, bought up the whole stock, and after investigating it came to the conclusion that the substance was not a new metal, but that it was an alloy of platinum and mercury with peculiar properties. In May 1803 Chenevix sent a paper to this effect to the Royal Society, which was read to the meeting by Wollaston, who was then one of the secretaries. Shortly afterwards an anonymous advertisement appeared in which a handsome reward was offered to any one who should prepare any of the new substance. No one succeeded in preparing any, and in the following year Wollaston announced that he was the discoverer of palladium, and described its preparation. He intimated at the same time his discovery of another new element, rhodium, now used for the electroplating of silver. Wollaston was the first to see the dark lines in the solar spectrum that have subsequently given us a knowledge of the nature of that wonderful body the sun, and helped us to understand the structure of atoms. He was also the first to explain why it is that when we look at a portrait hanging on a wall in a room, the eyes seem to look at us, in whatever part of the room we happen to be. The explanation is really a mathematical deduction from the rules of perspective.

Chevreul, a French chemist, made a very careful examination of fats between the years 1811 and 1823; he found that the fats are mixtures of compounds of glycerine, the

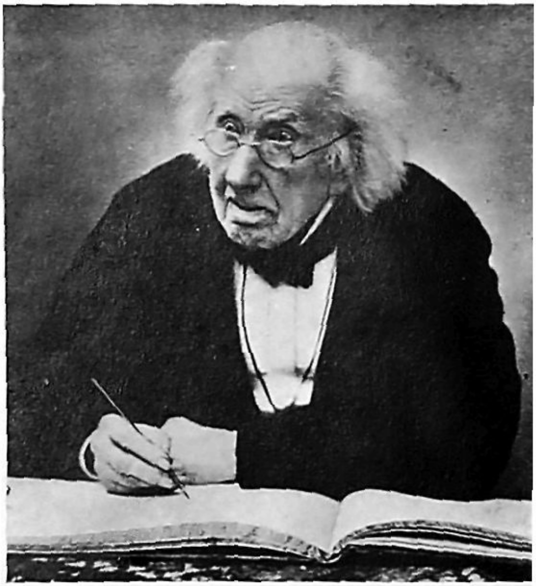
PLATE I



THE LABORATORY.

To William Pitcairn M.D. This Plate is Inscribed by his Gratefull
and Obliged humble Servant Thos. Major

HENRY
CAVENDISH



MICHEL
EUGÈNE
CHEVREUL

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Chemical Society*

principal of which are the stearates, the oleates, and palmitates of glycerine. These are complicated substances referred to in a later chapter. Chevreul was born in the year 1786, and died in 1889, in his hundred and third year. A writer who visited him in 1874 stated: "He is constantly at work, allowing only ten minutes for each of his meals, of which he has but two a day . . . except a small loaf at noon, which he eats standing and by the side of his alembics." He said on this occasion: "I am very old, and I have a great deal to do, so I do not wish to lose my time in eating." (See Plate II.)

Some of the chemists had their early struggles. Pelouze in his younger days was so poor that he lived for a time on bread and water, in a room so small that he had to open the window in order to put on his coat. Pelouze was one of the first chemists to study the effect of nitric acid and sulphuric acid on cellulose; and he was the first to show that the sugar in beetroot is the same as that in the sugar-cane. Cellulose is the principal constituent of cotton and of paper; from cellulose are made artificial silk, cordite, varnishes, and other important articles.

The advancement of scientific knowledge is the work of many men, some pointing the way to a path leading into the unknown, uncharted land, some toiling step by step along the path, opening up fresh possibilities. Dalton could not have discovered the broad highway of atomic theory along which we advanced so rapidly had not Cavendish, Priestley, Scheele, and Lavoisier preceded him. Lavoisier could not have reduced the infant science to a state of order had not a score of diligent workers collected a number of facts from which his genius deduced a system. After the time of Dalton we understood chemical combination far better than ever before. We think of sulphur as composed of an almost infinite number of sulphur atoms, of equal size and weight, each one weighing 32 times as much as a hydrogen atom. The atoms of sulphur are nearly indivisible, and until comparatively recent years it was thought that they could not be divided. We now know that by elaborate instruments it is possible to break up such an atom and to produce particles far too small to be seen with the help of a microscope, but these particles are not sulphur. When sulphur combines with hydrogen we picture one sulphur atom as attracting to itself two hydrogen atoms so firmly that they cannot escape. In this way is formed a molecule of hydrogen sulphide or sulphuretted hydrogen, an unpleasant-smelling substance that is given off by rotten eggs, and can be made in other ways. A fragment of iron is an assembly of a number of atoms of iron each atom weighing 55·8 times as much as an atom of hydrogen. So too every other element is composed of atoms of that element. The various chemical compounds are formed of almost infinitely small molecules consisting of two, three, or four atoms of different elements in the case of the simple compounds and twenty, fifty, or a hundred, or many more atoms belonging to perhaps eight or ten elements in the case of the more complex compounds. Many of the substances found in living creatures seem to be even more complex than this. Thousands of experiments carried out day by day for more than a hundred years by a multitude of chemists in many countries have proved beyond doubt the essential truth of Dalton's theory; that in a few details it requires a little modification need cause us no surprise.

CHAPTER II.

THE CHEMISTS' SIGNS AND SYMBOLS

EVERY science must have its special words, its own short-hand, and its own diagrams. Chemistry is no exception; the various chemical elements are mentioned so frequently that it is convenient to have a symbol to represent them, usually the first letter of the English or the Latin name, or the first and another letter; thus we use N for nitrogen, S for sulphur, Sn for tin (stannum), C for carbon, H for hydrogen, O for oxygen, Cd for cadmium, and so on. This device, which saves much time and space, was first used by the English chemist Thomson, and developed by the Swedish chemist Berzelius, in 1811. The next step was to try to construct formulæ which would indicate the way the various atoms are combined together in different compounds. Chemical compounds are peculiar substances; they are quite different from mixtures. If you mix the elements iron and sulphur together, first reducing each to a state of fine powder, you will obtain something that resembles both iron and sulphur to a certain extent, but it remains a mixture that can easily be separated into its two parts; you can remove the tiny particles of iron by a magnet and leave the sulphur, or you can dissolve the sulphur in a suitable liquid and leave the iron. But if the iron and sulphur are heated together, they will combine chemically, to form a compound, and you cannot remove the iron by a magnet nor dissolve the sulphur in a liquid. The separate atoms of the iron—too small even to be imagined—are firmly united to the separate atoms of the sulphur, and the compound possesses quite different properties from those of iron and sulphur.

You may mix the colourless gas oxygen with the colourless gas hydrogen, and you get a colourless gas; but if oxygen and hydrogen are mixed and an electric spark is made in the mixture, the gases will chemically combine, and the result is a colourless liquid—water. So, too, the black solid carbon can be made to combine chemically with the colourless gas hydrogen and produce the colourless gas acetylene. The silvery-grey metal lead will combine with the colourless gas oxygen to form the solid red lead.

The difference between a mixture and a chemical compound is often more than a difference in degree. In a mixture of two solids you are bringing into contact small particles perhaps as small as a thousandth part of a drop of water. In a chemical compound you are bringing into contact atoms or molecules, and these are so much smaller than drops of water that it is hard to imagine them. There are about as many atoms or molecules in a drop of water as there are drops of water in the Atlantic Ocean.

We have known for more than a century not only hundreds of chemical compounds, we have also learned the exact proportions in which the elements combine together in such compounds. We must go a stage further; it is not sufficient for us to know that two atoms of carbon and six atoms of hydrogen and one atom of oxygen unite to form one molecule of alcohol, C_2H_6O. We must know whether the two carbon atoms are united together, or whether they are separated by an atom of oxygen.

It was a slow and difficult business to find out how the various atoms in a compound are arranged in space and how they can be most conveniently represented by a diagram on a flat surface like the page of a book, and we are not surprised that from the time that Berzelius made symbols popular in 1811 until structural formulæ came into use a period of nearly fifty years elapsed.

A list of the symbols of all the elements will be found on pages 50 and 51; just at the moment it will suffice to have a list of some of the most frequent:

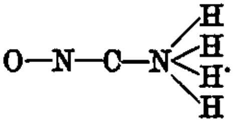
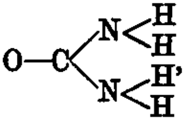
Al	Aluminium
C	Carbon
Cl	Chlorine
Cu	Copper
Au	Gold
H	Hydrogen
I	Iodine
N	Nitrogen
O	Oxygen
P	Phosphorus
Si	Silicon
S	Sulphur

When we write H_2O we mean that two atoms of hydrogen are combined with one atom of oxygen; SO_3 means one atom of sulphur combined with three atoms of oxygen; HNO_3 means a compound of one atom of hydrogen, one atom of nitrogen, and three atoms of oxygen.

It was found out in quite early days—that is to say, before 1830—that there were groups of atoms such as those now recognized as SO_4, NO_3, NH_4, and CH_3, that were very frequently met with in chemical compounds. Another group consisting of one carbon atom, two oxygen atoms, and one hydrogen atom is a very common one, and it is denoted by COOH or CO_2H, these being different ways of printing the same group. In course of time even more complicated groups were readily identified—for instance, C_2H_5, a group common to alcohol and ether, and C_6H_5, a group common to benzene, naphthalene, carbolic acid, and many other substances. When some thousands of different compounds had been analysed and prepared, it became possible to refer some of them to certain types or groups, and so a rough classification was gradually built up.

In 1824 the German chemist, Liebig, discovered that two quite distinct chemical substances, called silver cyanate and silver fulminate, though they had quite different properties, had the same numbers of atoms of silver, carbon, oxygen, and nitrogen, and that each could be represented by the formula AgCNO. This is now explained as follows: silver cyanate is Ag—C—N—O, but silver fulminate is Ag—O—C—N. It makes all the difference in the world whether the chain that consists of one carbon atom, one nitrogen atom, and one oxygen atom, is attached to the silver atom, shown as Ag, by the carbon atom or the oxygen atom. The group —C—N—O is a stable group when the C is attached to a suitable element or group. Silver cyanate is therefore a stable substance. But the group —O—C—N is an unstable group, and when it is connected to almost any atom, the compound readily breaks up. All the compounds called fulminates contain this —O—C—N group, and they explode very easily. One of the fulminates —fulminate of mercury—formed the essential part of the paper caps that we fired in toy pistols when we were small boys, and has a more important use as a detonator for high explosives.

We spoke earlier in this chapter ot some groups of atoms that are frequently found in chemical compounds, and we mentioned the group NH_4 as one of these. This group, consisting of one atom of nitrogen and four atoms of hydrogen, forms a part of many compounds. It is closely related to the ammonia vapour the smell of which is familiar to us all. Ammonia vapour is a compound of one atom of nitrogen and three atoms of hydrogen, and it is written NH_3. When ammonia vapour is brought into contact with water, it unites with it. We know that water is a compound of hydrogen and oxygen, and that its formula is usually denoted by H_2O; this fact is known to every schoolboy, and, we suppose, to every schoolgirl. The combination of NH_3 and H_2O gives us NH_5O, which is usually denoted NH_4OH; this substance is called ammonium hydroxide.

The liquid ammonia familiar to housewives is ammonium hydroxide diluted with water. It is quite easy to prepare a compound of nitrogen, hydrogen, and chlorine, having the formula NH_4Cl; this substance is known as sal-ammoniac, or ammonium chloride, and is used in the common electric cells we keep for our electric bells. $(NH_4)_2SO_4$ is what is commonly known as sulphate of ammonia, a fertilizer of great value. Chemists call it ammonium sulphate, and they call the group NH_4 ammonium. Just as there is silver cyanate, Ag—C—N—O, so there is ammonium cyanate, NH_4—C—N—O. In 1828 the German chemist, Wöhler, showed that ammonium cyanate and urea, with quite different properties, could each be denoted by the formula CON_2H_4. Obviously there was more than one way of arranging these atoms in space, and it is now quite well established that whatever is the actual space arrangement, the atoms in ammonium cyanate are connected together thus:  The formula for urea presents some difficulties; it may be approximately denoted by  but other modifications have been suggested. It can be seen that there are at least two ways in which two atoms of nitrogen, four atoms of hydrogen, one of oxygen, and one of carbon can combine together. If, with all our modern appliances and the inheritance of a hundred years of accurate experiment, we have only within the last two or three years agreed upon the structure of a simple substance like urea, we must not be surprised that chemists eighty and ninety years ago found it very difficult to agree on such matters.

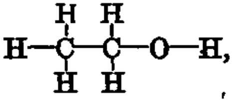
It was soon found out that such compounds, agreeing in the number of the various atoms composing them, but differing in their chemical properties, are very abundant among the compounds of carbon. Berzelius investigated several such compounds about the year 1830, and he called such bodies isomers. The existence of isomers cannot be said to assist in finding structural formulæ, except in the sense that such bodies cry aloud for an explanation and call attention to the need for satisfactory formulæ. The case of tartaric acid, investigated by Berzelius in 1830, is rather complicated; he found that the two kinds of tartaric acid then known were exactly similar in chemical properties and had formulæ each of which could be denoted by $C_4H_6O_6$, but they differed from each other in one singular physical property.

Another path towards structural formulæ resulted from a remarkable occurrence in the career of the French chemist Dumas about the year 1830. At a soirée in the palace of the Tuileries the guests were greatly annoyed by irritating fumes that came from the wax candles used to light the rooms. Dumas was asked to investigate the cause of the trouble; he found that the wax had been bleached by chlorine, and that the objectionable fumes contained hydrochloric acid.

He was led in this way to investigate the effect of chlorine, bromine, and iodine on a number of fats and other substances, and by-and-by he discovered this law: when a compound of carbon, oxygen, and hydrogen is treated with chlorine, bromine, or iodine, these bodies generally set free hydrogen, and for one atom or equivalent of hydrogen liberated there is retained in the compound one atom or equivalent of chlorine, bromine, or iodine.

In time Dumas came to hold the view that the main structure of a compound could persist and many of the properties remain unaltered, even if one or more hydrogen atoms were replaced by chlorine atoms, or by simple groups of atoms. This led to attempts to find out what was the nature of the main structure. The substitution theory, though now universally accepted, was scoffed at by the German chemists in 1840, and caused some sarcastic and amusing correspondence to be written.

Another consideration was found to be very helpful. It was noticed by Cavendish that one volume of oxygen would combine with two volumes of hydrogen to form water. It was found by Berthollet that two volumes of ammonia could be converted into one volume of nitrogen and three volumes of hydrogen; and it was found by Regnault that one volume of nitrogen can be made to combine with three volumes of hydrogen to form ammonia. Many elements combined with oxygen in two, three, or more different proportions, and very gradually it became recognized that for every element there was a maximum number of atoms of oxygen, or of hydrogen, or of chlorine it could combine with. This combining power gradually became apparent to chemists, about the year 1850, particularly to the English chemists Williamson and Frankland, and to the French chemist Gerhardt. Frankland clarified the whole situation, and gave the name of " valency " to the combining power. He divided the elements into classes: those which would combine with one atom of hydrogen or chlorine (monovalent elements), those which would combine with two, or three, or four, or five such atoms and so on. The valency of an element is not necessarily a fixed quantity; an element that can combine with five monovalent elements can perhaps combine with three, sometimes—though less usually—with four. Hydrogen, potassium, and sodium are monovalent elements; magnesium and calcium are divalent; aluminium is trivalent; carbon is tetravalent; nitrogen, arsenic, and phosphorus are pentavalent; sulphur is hexavalent, and manganese is heptavalent. No element has a valency greater than eight. Valency is an intricate and difficult property to discuss, but its main principles are plain and simple, and the classification of elements according to their valency was a very convenient and useful step to take. It was really the last step that enabled chemists to picture to themselves the way in which atoms are built together, and to draw diagrams, or structural formulæ, representing, so far as they can—and it is not always very far—the arrangement in space of the various atoms in a chemical compound. Although it is very convenient to treat the elements as having each a definite valency, this is only a rough and useful classification; in the main it is true, but there are so many exceptions that we are unable to lay down a strict law.

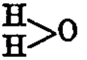
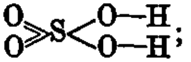
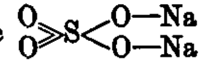
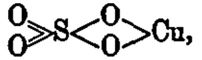
In the year 1858 a young Scots chemist, Archibald Scott Couper, and an older and more famous German chemist, August Kekulé, independently put forward a number of structural formulæ, and when, in 1860, Odling, the professor of chemistry at Oxford, used lines to denote the valencies—one line for a monovalent element, two lines for a divalent element, and so on—the diagram system was complete. Henceforward we could denote alcohol as  $\mathrm{H{-}\overset{H}{\underset{H}{C}}{-}\overset{H}{\underset{H}{C}}{-}O{-}H}$, to show how the atoms are connected together in alcohol, although this does not represent how they are arranged in space. The spatial arrangements could not be found out until the work of van 't Hoff and Le Bel, fourteen years later. This is explained on p. 83.

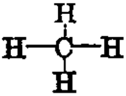
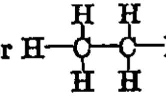
The valency of an element is found by the analysis of its compounds; hydrochloric acid gas, HCl, contains 35·5 times as much chlorine by weight as it does hydrogen, and in all the many compounds in which an atom of hydrogen can be replaced by an atom of chlorine the weight will be increased by a figure that corresponds with this difference between the two weights. It was easy to make a list of the proportions in which thirty or forty chemical elements would combine, and such lists grew steadily in length and in accuracy during the first half of the nineteenth century. But one fundamental figure remained doubtful—that is, whether the combining weight of oxygen should be considered as 8 or as 16. Chemists were not agreed on this, for by assuming a suitable number of oxygen atoms in the compound, either combining weight or atomic weight could be made to fit; and the chemists did not, as we now do, clearly distinguish between molecules and atoms.

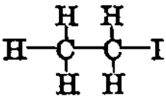
This doubt applied to some of the other elements besides oxygen, but once the question of oxygen was settled, the same reasoning settled the atomic-weight of the other elements.

We use the term atom to denote the smallest possible particle of an element; we now use the term molecule to denote the smallest particle of a gas or any other definite chemical substance that can have a separate existence; it usually consists of a small number of atoms. This use of the word molecule is due to Avogadro, who showed how it was possible to decide the doubtful question of the atomic weight of oxygen. His views long remained unknown to most chemists and unheeded by the others. He was a physicist, and did not mix with the chemists of his day; besides which, they were not at that time much interested in his theory.

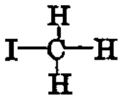
In 1860 there was a Congress of Chemists at Carlsruhe, and one of the points they discussed at considerable length was whether it would be judicious to establish a difference between the terms atom and molecule. Among those who spoke was the Sicilian chemist Cannizzaro, who two years previously had written a pamphlet on the theory of Avogadro, its usefulness and truth; copies of this pamphlet were circulated at the meeting, and the principles of Avogadro were adopted; henceforward the atomic weight of oxygen was almost universally accepted as sixteen times that of hydrogen, and the long list of atomic weights has since been freed from the ambiguity it previously possessed. At this conference one of Cannizzaro's pamphlets was handed to the German chemist Lothar Meyer, who recorded his impression of it as follows: "I also received a copy which I put in my pocket to read on the way home. Once arrived there, I read it repeatedly, and was astonished at the clearness with which the little book illuminated the most important points of controversy. The scales fell from my eyes. Doubts disappeared, and a feeling of quiet certainty took their place. If some years later I was able to contribute something towards clearing up the situation and calming heated spirits, no small part of the credit is due to this pamphlet of Cannizzaro."

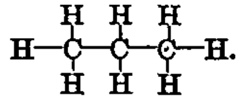
We may illustrate the way in which various atoms combine together by a few examples. Sulphur is a hexavalent element, and forms a trioxide  $O{=}\underset{\underset{O}{\|}}{S}{=}O$; this trioxide combines with water  $\begin{matrix}H\\H\end{matrix}\!>\!O$ to form sulphuric acid  $\begin{matrix}O\\O\end{matrix}\!\gg\!S\!<\!\begin{matrix}O{-}H\\O{-}H\end{matrix}$; various sulphates are easily made, sodium sulphate  $\begin{matrix}O\\O\end{matrix}\!\gg\!S\!<\!\begin{matrix}O{-}Na\\O{-}Na\end{matrix}$ and so on. The blue crystals of copper sulphate contain not only copper sulphate $CuSO_4$, but also a certain amount of water, five molecules of water to one molecule of $CuSO_4$. We know how the atoms are compounded together in a molecule of $CuSO_4$; it is thus  $\begin{matrix}O\\O\end{matrix}\!\gg\!S\!<\!\begin{matrix}O\\O\end{matrix}\!>\!Cu$, and a molecule of water is H—O—H; but we do not know exactly how the water and the copper sulphate are combined together in the blue crystals; there is a looser sort of combination between the water and the copper sulphate in these crystals than there is between the sulphur and the oxygen in the molecule of copper sulphate. Some crystals—common salt, NaCl, is an instance—contain no water; some crystals—for example, those of alum—contain a great deal. Crystals of alum are aggregates of potassium sulphate, aluminium sulphate, and water, assembled in a definite manner, which does not vary, and gives us the familiar octahedral crystals. Structural formulæ truly denote simpler units than are found in crystals; sometimes they represent what you would see if you could cut a thin section of a crystal, sometimes they represent an imaginary isolated unit of a crystal. It is, in fact, often impossible to represent a crystal that spreads in three dimensions by a flat structural formula; you may give a clue to the spatial arrangement in this way, but not a picture. And what we have stated of crystals is true, with some modifications, of all solids. In our desire to obtain simplicity by using structural formulæ we sacrifice something in accuracy. But when we are dealing with solid compounds, if we regard the structural formulæ as clues or guides only we shall find them extremely useful companions. We must not regard ice as a collection of little molecules of H—O—H; ice is more complex than that.

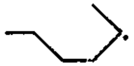
Postponing for a time a more detailed account of crystals, we will give some more instances of classes or types of chemical compounds. Dalton showed that methane, the fire-damp of coal-mines, is a compound of carbon and hydrogen, CH_4 or  $H-\overset{H}{\underset{H}{C}}-H$; another gas that is very familiar to chemists is ethane, C_2H_6 or  $H-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}-H$. Just as Dumas showed how to substitute an atom of chlorine for one of hydrogen in many substances, so chemists have long been able to substitute an atom of iodine for one of hydrogen and to make

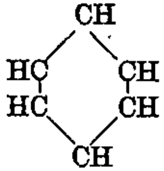

$$H-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-I$$

and


$$I-\underset{H}{\overset{H}{C}}-H$$

The metal sodium has a great attraction for iodine, and if it is added to a mixture of the two substances whose formulæ are given above, it takes away both the atoms of iodine and leaves the residues to combine together to form a new compound  $H-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-H$. This process may be repeated many times, so that we can obtain a chain with a dozen or more carbon atoms in it. Mixtures of such compounds, with chains of eight, nine, ten, and more carbon atoms, form the liquids familiar to us as petrol and paraffin. It is not necessary for chemists to manufacture these liquids in the way we have mentioned, for they are found in enormous quantities in the earth, resulting probably from the decomposition of vegetable matter hundreds of thousands of years ago.

Although it is convenient to print these chains as if they were straight, they are not straight in fact, but bent sometimes thus:  or thus: . There is a great series of compounds of carbon and hydrogen founded on a hexagonal ring of carbon atoms. This simple ring compound is the familiar benzene or benzol which is used as a fuel for our cars. It was discovered by Faraday in 1825; it was found to contain six atoms of carbon by Mitscherlich, who named it benzine; Kekulé showed that the six carbon atoms were united in a hexagonal ring thus:—

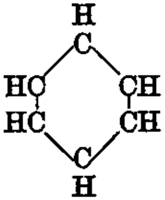


To illustrate the vagueness of thought about atoms and molecules, we will quote two famous passages from the reminiscences of August Kekulé. He was born in 1829, and after studying chemistry in Germany, he came to London in 1854 and stayed for some months. Here he became intimate with Williamson and Odling, and from these, and especially from Williamson, he learned a great deal. He himself recorded the following incident. "During my stay in London I resided for a considerable time in Clapham Road in the neighbourhood of the Common. I frequently, however, spent my evenings with my friend Hugo Muller at Islington, at the opposite end of the giant town. We talked of many things, but oftenest of our beloved chemistry. One fine summer evening I was returning by the last omnibus 'outside' as usual, through the deserted streets of the metropolis, which are at other times so full of life. I fell into a reverie and Lo, the atoms were gambolling before my eyes! Whenever, hitherto, these diminutive beings had appeared to me they had always been in motion; but up to that time I had never been able to discern the nature of their motion. Now, however, I saw how, frequently, two smaller atoms united to form a pair; how a larger one embraced two smaller ones; how still larger ones kept hold of three or even four of the smaller; whilst the whole kept whirling in a giddy dance. I saw how the larger ones formed a chain, dragging the smaller ones after them, but only at the end of the chain. I saw what our Past Master, Kopp, my highly honoured teacher and friend, has depicted with such charm in his 'Molekularwelt'; but I saw it long before him. The cry of the conductor: 'Clapham Road' awakened me from my dreaming; but I spent a part of the night in putting on paper at least sketches of these dream forms. This was the origin of the structure theory."

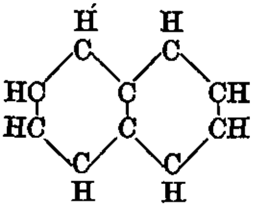
At a later date, presumably in the early sixties, when Kekulé was professor at Ghent, he dreamed again. "I was sitting, writing at my text-book; but the work did not progress; my thoughts were elsewhere. I turned my chair to the fire and dozed. Again the atoms were gambolling before my eyes. This time the smaller groups kept modestly in the background. My mental eye, rendered more acute by repeated visions of this kind, could now distinguish larger structures, of manifold conformation; long rows, sometimes more closely fitted together; all twining and twisting in snake-like motion. But look! What was that? One of the snakes had seized hold of its own tail, and the form whirled mockingly before my eyes. As if by a flash of lightning I awoke; and this time also I spent the rest of the night in working out the consequences of the hypothesis." "Let us learn to dream, gentlemen," added Kekulé; "then perhaps we shall find the truth—but let us beware of publishing our dreams before they have been put to the proof by the waking understanding."

From this dream Kekulé gradually developed his theory of the benzene ring which he published in 1865; it has stood the test of time, and is universally accepted.

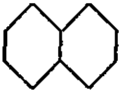
We can prepare not only benzene, but also many other substances in which there are six carbon atoms combined

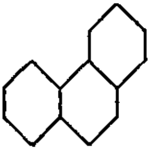


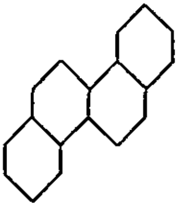
together in a ring—for instance, the naphthalene that we use *to drive away the moths from our clothes has this formula :*



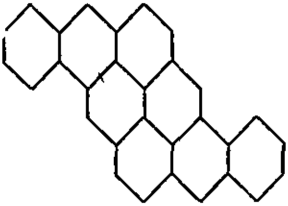
If, to save space, we denote six carbon atoms in a ring by a simple hexagon, we may say that chemists can construct compounds belonging to the following types in endless variety :







and so on up to



Moreover, in such compounds we can substitute a chlorine atom for a hydrogen atom, or a CH_3 group for a hydrogen atom; in some compounds containing such rings we can substitute an oxygen atom or a sulphur atom for one of the carbon atoms, and so obtain a very large number of new compounds. The majority of such new compounds will be substances of no interest except to chemists, but perhaps one in a hundred turns out to be a useful dye or a valuable drug.

It is a very remarkable achievement that chemists by a logical and lengthy process should be able to build together various substances of so high a degree of complexity, and that they can prepare in this way dyestuffs, and drugs, of great value. It is equally worthy of note that substances of an even greater degree of complexity are accurately made by plants and animals without the use of artificial apparatus, high pressures, or high temperatures. We know much about the chemical processes that lead to, or accompany, or perhaps are the growth of plants and animals, but there is much to learn that we are at present quite unable to understand.

The formulæ, of which we have given a few examples, do not in most cases give, or even attempt to give, an indication of how the various atoms of a compound are arranged in space. All that these diagrams show is which atom is specially attracted by or attached to some other atom; this can often be demonstrated with great certainty.

CHAPTER III

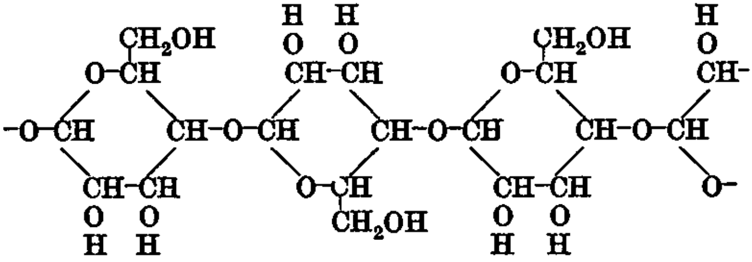
HOW MATTER IS BUILT UP

It is interesting to know how simple substances like silver cyanate and copper sulphate are built up and how the various atoms that compose them are united, but these substances are unfamiliar to most of us and we may as well face the structure of substances to be found in every house and garden. It is true that they are a little more complicated, but as it is only the principles that we are concerned with, and not the details, there does seem to be some justification for treating of substances such as cellulose, which is the main constituent of paper and cotton, and discussing the rocks of which our mountains are made, and fats, and soap, and the Bakelite resins, and india-rubber. These are typical of an enormous number of other substances to be found in the animal, vegetable, and mineral world. The daffodil, the worm, the human being, wood and coal are mainly composed of substances of the same degree of complexity as cellulose and fats, and a few examples will suffice to illustrate structures that account for perhaps 90 per cent. or more of the crust of the earth and the animals and plants living on it.

Many of the substances prepared by chemists in their laboratories are simple units composed of a definite number of atoms, and they have definite chemical formulæ. The substances we treat in this chapter are aggregates of simple units, but the aggregates have no definite number of atoms, and no definite chemical formulæ. We use the word aggregate to denote collections of smaller units chemically combined together and such aggregates are in some cases chains of indefinite length, or sheets of indefinite length and breadth, or masses of indefinite length, breadth, and thickness.

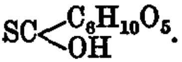
Because of this indefinite character, and perhaps for other reasons also, there are more varieties of such substances than there are of the simple laboratory chemicals. There are several varieties of cellulose, perhaps a score of varieties of starch, and many varieties of such common minerals as felspar and garnet.

Cellulose is contained in all plants, and it forms a considerable proportion of cotton and wood fibre; it is the principal constituent of paper, and is the foundation of the modern artificial silk or rayon. Cellulose is a compound of carbon, hydrogen, and oxygen, and it consists of long chains of this nature:



No doubt when two or three of these chains lie alongside each other there is an attraction between some of the atoms in one chain and the atoms in another chain; this attraction is of the same nature as chemical combination. It took a long time to learn how to make artificial silk from cellulose on an industrial scale; by chemical methods it is not difficult to make from cellulose a gummy fibre that will quickly dry and become hard, but the picking up of the threads as they are made and the spinning of them furnished the manufacturers with problems that took them years to solve.

A hundred years ago it was found that sulphuric acid and nitric acid would act upon cellulose to form a compound called nitrocellulose. The first to make any useful threads of artificial silk was Sir Joseph Swan, who dissolved nitrocellulose in acetic acid and squirted it through a small hole. When it dried it formed threads, and these his wife crocheted into lace; a few articles so made were exhibited at the Inventions Exhibition of 1885, but he did not develop his invention on a commercial scale. The first factory to make artificial silk was one erected in France by Count Hilaire de Chardonnet in 1891.

There are two principal methods of making artificial silk that are employed on a large scale in England, one for making "viscose" and one for making "celanese." Viscose was invented in England in 1892 by Cross, Bevan, and Beadle, and after fourteen years of experimenting and the spending of a great deal of money was commercially developed by Messrs. Courtauld about the year 1906. In this process the cellulose is treated with caustic soda and then with carbon disulphide, a compound of carbon and sulphur; and each of the rings of the cellulose chain, instead of being $C_6H_{10}O_5$, is converted into this:  $SC<^{C_6H_{10}O_5}_{OH}$. A further simple treatment converts it into viscose fibres. More than half the world's output of artificial silk is made by the viscose process.

Celanese is made by treating cellulose with acetic acid by a process originally discovered by Cross and Bevan in 1894 and improved by Miles in Boston, U.S.A., and by Messrs. Dreyfus in Switzerland.

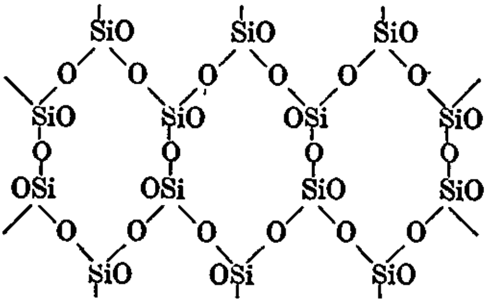
Nitrocellulose is of commercial importance apart from its use in the manufacture of artificial silk. The waste from a cotton factory consists mainly of cellulose, and if it is treated with nitric acid containing a proportion of sulphuric acid, there is formed a mixture of nitrocelluloses (compounds of cellulose and nitric acid). We need not now concern ourselves with the part played by the sulphuric acid in the process. The powerful explosive gun-cotton consists of nitrocellulose; when glycerine is treated with nitric acid an explosive called nitroglycerine is obtained; this was once largely used in mining and quarrying. If gun-cotton is dissolved in nitroglycerine, the important explosive " cordite " is obtained.

A very important class of compounds is that of the silicates, compounds of silica with such elements as sodium, potassium, aluminium, and iron. Silica is an oxide of silicon, SiO_2, and it occurs as the well-known minerals called quartz, rock-crystal, carnelian, agate, cairngorm, and amethyst. Compounds of silica with potassium and aluminium form such common minerals as the felspars which constitute about 60 per cent. of all the granites, syenites, and other volcanic rocks; mica is another silicate of potassium and aluminium that forms thin transparent sheets.

In quartz there are two atoms of oxygen to each atom of silicon, and these are spread out regularly in space, so that each silicon atom is attached to four oxygen atoms, which are attached to another silicon atom that is itself attached to four oxygen atoms, and so on. It is impossible to show this arrangement conveniently on a flat diagram. Felspar is similarly arranged, except that potassium atoms and aluminium atoms are inserted in the vacant spaces, one of each of these to each three silicon atoms.

In the crystals of quartz and felspar each atom is attached to all the atoms that surround it, and the atoms are fairly regularly situated in space, so that the crystals are hard and tough.

Mica is differently arranged; in this the silica is spread in flat rings of this nature so as to form a sheet:



and in the vacant spaces are inserted atoms of potassium and aluminium, and also some groups of OH, oxygen, and hydrogen, called hydroxyl groups.

No doubt there is an attraction between one flat ring of mica and a flat ring lying above it or below it, but this is not so strong an attraction as that between one mica ring and another lying alongside it. A much greater force is necessary to separate the three rings shown in the above diagram from each other than to separate one sheet from another; consequently mica is easily split into thin transparent layers, parallel to the flat rings, and such transparent tough mica plates are familiar objects. They formerly formed parts of the wind-screens of cars, and can still be seen in anthracite stoves.

Granite is a volcanic rock that consists of a mixture of crystals, often large crystals a quarter or half an inch wide, of felspar, with smaller crystals of quartz and mica. In granite the felspar crystals are often pink, and the mica appears as small glistening scales. Sandstones are made up of worn and broken crystals of silica, and many great ranges of mountains are mainly composed of silica and the silicates; for instance, the mountains in the Highlands of Scotland and the Coolin Hills in Skye are of this nature.

The hills of Derbyshire, and the Yorkshire Dales contain many beds of limestone, or calcium carbonate, $CaCO_3$.

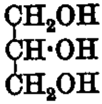
When this is heated, carbon dioxide is driven off, and lime, CaO, is left. In addition to the use of lime to spread upon the land, where it replaces the calcium that is washed away by years of rain, lime is largely used to make mortar. The lime is mixed with sand and then with water, forming a wet mixture of sand and calcium hydroxide, $Ca(OH)_2$. When this is spread upon brick or stone, the excess of water evaporates, leaving an intimate mixture of solid calcium hydroxide and sand, and the hydroxide slowly absorbs a little carbon dioxide from the air, making again calcium carbonate, $CaCO_3$, and forming a hard substance.

Limestone is entirely of living origin. It was deposited at the bottom of a sea, and consisted originally of particles of shells, corals, weeds, and other remains. The calcium carbonate contained in these has persisted, often retaining the original structure that we can see in the limestone fossils, but sometimes the limestone loses all trace of fossil structure and gradually becomes crystalline, as we may notice in some varieties of marble. The atoms in the solid limestone are not perfectly at rest, though they seem to be. After a long course of many thousands of years, the limestone tends to become more crystalline, and the process is more rapid when the rock is subjected to changes of pressure and temperature. A slight power of movement of the atoms can be detected in many crystalline bodies, and it is of some importance in the case of metals and alloys, and is mentioned later in this book.

It would be quite impossible in any book smaller than the *Encyclopædia Britannica* to give an account of all the chemical compounds that are known to exist; we have chosen a very few instances, that illustrate some of the ways in which substances are constructed, and we must refer the reader who wishes to pursue the subject further to the ordinary text-books of chemistry. But we will give one or two more examples: first, a common household article, soap. The ordinary hard soaps that we use are mixtures, and not chemical compounds; they are mixtures of various substances, three of which form the great bulk of our common soaps. From such fats and oils as tallow, *suet*, *copra*, *olive oil*, and palm oil, there may be obtained what are called "fatty acids," and three of the commonest of these are palmitic acid, stearic acid, and oleic acid. It is not essential for us to remember their formulæ, but it is desirable to know the general nature of these fatty acids, and so we give their formulæ. Palmitic acid and stearic acid consist of long chains of CH_2 groups, with a CH_3 group at one end and a COOH group at the other end, stearic acid having two more CH_2 groups than palmitic acid. Stearic acid has the formula $C_{17}H_{35}COOH$ and palmitic acid $C_{15}H_{31}COOH$. Oleic acid, which is easily obtained from olive oil, resembles stearic acid, but two of the CH_2 groups are replaced by CH groups and its formula is $C_{17}H_{33}COOH$.

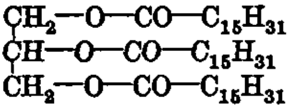
It is customary in chemistry to use CH_2 to denote a group of one carbon atom and two hydrogen atoms, and to use COOH, and not CO_2H, to denote a group of one carbon atom, two oxygen atoms, and one hydrogen atom. The reason for this is that the COOH group is really $-\mathrm{C}{<}^{\mathrm{O}}_{\mathrm{O-H}}$, and it is convenient to have a symbol that calls attention to the fact that OH forms an essential part of the group.

The oils and fats from which these acids are prepared are themselves mixtures of compounds of the fatty acids with glycerine. Glycerine, which was discovered by Scheele in 1779, has this constitution:



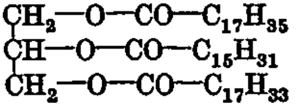
$$\begin{array}{l}\mathrm{CH_2OH}\\ |\\ \mathrm{CH{\cdot}OH}\\ |\\ \mathrm{CH_2OH}\end{array}$$

If we take palmitic acid as an example, we find that a fat that is a compound of glycerine and palmitic acid would have this constitution:



$$\begin{array}{l} CH_2-O-CO-C_{15}H_{31} \\ | \\ CH-O-CO-C_{15}H_{31} \\ | \\ CH_2-O-CO-C_{15}H_{31} \end{array}$$

This is a possible fat, but those found in nature are usually mixtures of fats of this type:



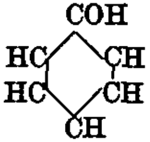
$$\begin{array}{l} CH_2-O-CO-C_{17}H_{35} \\ | \\ CH-O-CO-C_{15}H_{31} \\ | \\ CH_2-O-CO-C_{17}H_{33} \end{array}$$

in which each fat is a compound of glycerine and two or three different fatty acids.

When such fats are heated with a solution of caustic soda in water, the fats undergo a chemical change and form glycerine and a mixture of stearate, palmitate, and oleate of soda. The proportion of these three last substances depends on the nature of the fats chosen for the manufacture. Being solid, the mixture of these three, forming the *soap*, is easily separated, the glycerine is distilled in order to purify it, and is then ready for sale.

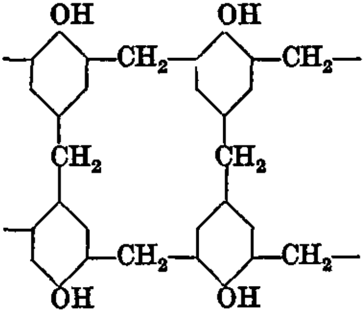
During the last few years a great industry has sprung up: the manufacture of cups and saucers, ash-trays, dishes, and other moulded articles made of artificial resinous materials called Bakelite, Beatl ware, and other trade fancy names. There is hardly a house, an office, or a motor-car in which there are not some articles made of these new materials. They are all made by pouring a moulding powder into a hot mould and then compressing it for a few minutes, so that it becomes a hard, solid substance. These moulding powders are of several different kinds: Bakelite is made by the interaction of phenol (carbolic acid) and formaldehyde;

phenol is a derivative of benzene and it has this formula:



formaldehyde is a much simpler substance, and has the formula CH_2O.

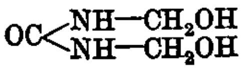
It is not yet possible to say what is the formula of the phenolformaldehyde resin, but it is an aggregate, spreading in three dimensions, of a fairly simple unit. The unit is of this nature; denoting the benzene ring by a simple hexagon:



The union of single units into an aggregate of many such units is called polymerization, and it is an extremely common phenomenon.

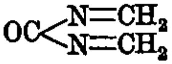
Beatl ware is made by the polymerization of a compound of urea and formaldehyde.

If we represent urea by this formula $OC<\begin{smallmatrix}NH_2\\NH_2\end{smallmatrix}$ it is considered that some such substance as this is formed:



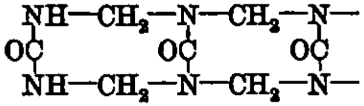
$$OC<\begin{matrix}NH-CH_2OH\\NH-CH_2OH\end{matrix}$$

or



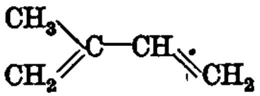
$$OC<\begin{matrix}N=CH_2\\N=CH_2\end{matrix}$$

and when this polymerizes it is believed that we obtain an aggregate in three dimensions with this sort of structure:

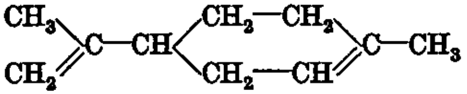


The structure of these resins formed by polymerization is by no means easy to determine with certainty.

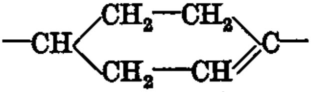
Another resinous material formed by polymerization is india-rubber, of which the principal ingredient is a hydrocarbon (compound of hydrogen and carbon) of which the unit is isoprene. Isoprene has this formula:



and the hydrocarbon of which india-rubber mainly consists is built upon this plan:



or an assemblage of links each consisting of



These few examples will probable suffice to show the ways in which chemical compounds are constructed. Such compounds as the gas carbon monoxide, water vapour, and ammonia vapour have very simple molecules; the liquids have molecules that are larger and contain more atoms; benzene, alcohol, sulphuric acid, and glycerine are instances of these. The solid bodies that we have considered are of different kinds: crystalline bodies in which there is perhaps a simple unit like silica, SiO_2, but in which these various units are attracted together to form sheets, or large aggregates having length, breadth, and thickness, and the substances have definite crystalline forms. Then there are the fats to which we have so recently referred. These are mixtures, but if we separate the glycerine palmitate from the other constituents, we find that it consists of large molecules containing a total of 51 carbon atoms, 98 hydrogen atoms, and 6 oxygen atoms—roughly 150 all told. These molecules lie in adjacent positions to each other, but there seems to be little or no attraction between one molecule and its neighbour in the oils and fats.

Another class of solid substances we have mentioned contains bodies in which a ring or chain is continually repeated almost indefinitely, and is connected by side-chains or chemical attractions, so as to make a tough, solid body—cellulose, Bakelite, starch, and india-rubber are examples of this class, and most of the solid substances in the vegetable and animal kingdom belong to it.

Many of the solid substances in the mineral kingdom belong to the crystalline class. It is not always easy to draw a sharp line of distinction between such classes. Coal is an instance; it consists mainly of the fossil remains of a swamp, peat bog, or forest, and it may preserve some of the vegetable structure, as we occasionally notice in bituminous coals, or it may lose this structure almost completely, as we see in anthracite.

Glass is a substance of no definite chemical composition; it is a mixture of silica and various silicates—for instance, sodium silicate, potassium silicate, calcium silicate, lead silicate, and aluminium silicate. Sometimes boron compounds (borates) are included in the mixture.

The quality and properties of the glass depend upon the particular substances included in the mixture and the proportions of them.

Window glass may contain about 13 per cent. of soda, 13 per cent. of lime, 70 per cent. of silica, and 3 per cent. of alumina, all intimately combined and mixed together in the molten state, so that one cannot properly speak of it as either a mechanical mixture or a definite chemical compound. In this respect it resembles porcelain, and earthenware, Bakelite, steel, starch, and cellulose. If you add more silica, or a proportion of potash or potassium silicate, to the molten glass, you will get a glass that has slightly different properties. There are two properties of glass that are of considerable importance and depend upon the proportions of the substances used in making it. One property is its transparency; all glass is transparent to some extent and lets the rays of light pass through it, but many varieties of glass exclude the ultra-violet rays which are beneficial to plants and animals, and some of the infra-red rays which give a certain amount of warmth. Another property of glass is that it expands on heating, and if it is very suddenly heated or suddenly cooled, the expansion or contraction is sufficient to break it or crack it, for it is a brittle substance.

Silica itself is fusible, and threads of fused silica can be made so thin as to be invisible to the eye, but strong enough to support a trifling weight. Silica only expands on heating one-seventeenth as much as ordinary glass, and a sheet of silica allows most of the ultra-violet rays to penetrate through it. If the proportion of silica in glass is increased to about 80 per cent., a glass is obtained that is not easily cracked by heat; Pyrex, now so much used in our kitchens, contains about 80 per cent. of silica, about 12 per cent. of oxide of boron, and a little soda and alumina.

Vitreosil, which is a pure silica, is even more resistant to changes of temperature; it looks like glass, but it can be heated red-hot and plunged into cold water without cracking. Vitreosil is to the chemist what Pyrex is to the housewife, and it allows even more of the ultra-violet rays to traverse it.

It would be much more satisfactory to the students of elementary chemistry if we could divide all substances into the distinct classes of mechanical mixtures and chemical compounds. Unfortunately such students were not considered when the world gradually cooled down from a mixture of hot gases and formed all kinds of solid and other bodies.

CHAPTER IV

FAMILY GROUPS

In almost every science there are far more workers than thinkers; nearly every student can be trained to make accurate observations and to discover new facts, and in a young science, as chemistry was a hundred years ago, there were plenty of new facts to be discovered by any diligent chemist. The classification of facts and the reduction of them to a state of law and order involve two conditions: that there are a sufficient number of the necessary facts accurately recorded, and that some one acquainted with the facts has sufficient ability and imagination to sit down quietly and puzzle out the connexion between them.

Dalton was such a thinker and the result of his meditations was the Atomic Theory. The next really important development that concerns us is known as the Periodic Table of Elements, and it was evolved about fifty years later than the Atomic Theory. It is not a difficult matter to explain now, but it was a very difficult matter in 1840 or 1850, and part of the difficulty arose from the circumstance that some of the facts necessary to establish the theory were not then accurately known. It seems hardly worth while to record the unsuccessful efforts made by a few chemists to find a definite classification of the various chemical elements before the time had really arrived. By the year 1860 it was possible to discover a general plan, and since then all the details have become known and can be fitted properly into the scheme.

At that time most of the common elements had been discovered, and after the Congress at Carlsruhe, as we have mentioned, their atomic weights were known with sufficient accuracy. Moreover, Sir Humphry Davy by electrical methods had isolated the metals sodium, potassium, calcium, and a few other elements, and several others had been subsequently discovered. Here is a list of the elements with the smallest atomic weights; all these were known in 1860, and their atomic weights were also known, but not quite so accurately as we know them now.

Element.	Symbol.	At. Wt.	Valency.
1. Hydrogen . .	H	1	1
2. Lithium . .	Li	7	1
3. Beryllium . .	Be	9	2
4. Boron . . .	B	10·8	3
5. Carbon . . .	C	12	4
6. Nitrogen . .	N	14	5
7. Oxygen . . .	O	16	2
8. Fluorine . .	F	19	1
9. Sodium . . .	Na	23	1
10. Magnesium . .	Mg	24	2
11. Aluminium . .	Al	27	3
12. Silicon . . .	Si	28	4
13. Phosphorus . .	P	31	5
14. Sulphur . . .	S	32	6
15. Chlorine . .	Cl	35·45	7
16. Potassium . .	K	39	1
17. Calcium . . .	Ca	40	2

It had been noticed as a curious fact that No. 2, lithium, No. 9, sodium, and No. 16, potassium, resembled each other very closely in their general chemical characteristics; the chlorides of these elements resemble each other very much; so do the nitrates, and indeed all the other compounds of them. Other resemblances were noticed; No. 3, beryllium, No. 10, magnesium, and No. 17, calcium, are chemically very similar. These three numbers differ from each other by 7. So, too, No. 8, fluorine, and No. 15, chlorine, form compounds that are very similar and the difference between 8 and 15 is 7.

The chemist Newlands in 1864 deduced from these and other facts what he called the "Law of Octaves," but although this law has a real foundation in fact, there were at that time so many omissions and so many exceptions that his "law" met with very little encouragement. The omissions were really due to elements then undiscovered and almost all these have since been discovered; the exceptions puzzled chemists for a long time, but now a reasonable explanation of them all can be given. It was the Russian chemist, Mendeléeff, who was the most successful in developing the rather crude ideas of Newlands into the complicated and satisfactory table we now use. This great piece of work was achieved about the year 1870.

In dealing with a complicated set of facts like the atomic weights and the valencies of the chemical elements, it is reasonable and proper to arrange the elements in the way that best brings out the various similarities that exist. Hydrogen is the lightest of all the elements, and when, early in the nineteenth century, it was found out that the atomic weight of carbon was 12, of nitrogen 14, and of oxygen 16, a theory was started that the other elements were all formed from hydrogen, but in different quantities, 12 units of hydrogen giving carbon, 14 nitrogen, and so on. But it was found that several of the elements had atomic weights that were not whole numbers—for instance, that of boron is 10·8 and that of chlorine 35·45. So many exceptions were found that the theory was, not exactly disbelieved, but put into cold storage to wait for some explanation.

Taking the elements mentioned on page 47, we arrange these as follows:

H	Li	Be	B	C	N	O	F
	Na	Mg	Al	Si	P	S	Cl
	K	Ca					

This classification of the elements into "octaves" brings the similar elements lithium, sodium, and potassium into one group, the similar elements beryllium, magnesium, and calcium into another group, and so on, and if only all the other elements were as obedient to the law the story could be told in a few words. But they are not.

Still, it is no use regretting the facts or shirking them; our business is to state them as accurately as possible and to explain them as simply as we can, and the latter is not a very easy thing to do.

In 1894 and the next few years some rare gases were found in the atmosphere—helium, neon, argon, krypton, and xenon. They form no chemical compounds and have no chemical activity; they are discussed in Chapter VIII, but they cannot be omitted from the Periodic Table of the Elements. The word Periodic is used to signify that the elements can be arranged in groups that recur at regular intervals on the lines already mentioned. There is another very awkward group of elements occurring chiefly in rare minerals found in Sweden and not found in any quantity anywhere else. There are fifteen of them; their atomic weights all lie between 138 and 175, and all the elements with atomic weights between these two numbers are these rare-earth elements. They are so similar to each other that their compounds are only separated with the utmost difficulty; most of these elements have never been prepared; only their compounds are known. Only one of them, the element cerium, is of any practical value. It is a silvery metal that can be alloyed with other metals, and when such an alloy is struck by a hard substance like flint or a steel wheel, a little flake of the alloy is knocked off and takes fire in the air, forming a spark that can set fire to a string or a wad of cotton-wool soaked in petrol. The familiar cigarette-lighters are constructed on this principle.

Let us now consider the Table of the Elements as it

	Group 1.	Group 2.	Group 3.	Group 4.
Period I	1. Hydrogen (H)			
Period II	3. Lithium (Li)	4. Beryllium (Be)	5. Boron (B)	6. Carbon (C)
Period III	11. Sodium (Na)	12. Magnesium (Mg)	13 Aluminium (Al)	14. Silicon (Si)
Period IV	19. Potassium (K)	20. Calcium (Ca)	21. Scandium (Sc)	22. Titanium (Ti)
Period V	29. Copper (Cu)	30. Zinc (Zn)	31. Gallium (Ga)	32. Germanium (Ge)
Period VI	37. Rubidium (Rb)	38. Strontium (Sr)	39. Yttrium (Y)	40. Zirconium (Zr)
Period VII	47. Silver (Ag)	48. Cadmium (Cd)	49. Indium (In)	50. Tin (Sn)
Period VIII	55 Cæsium (Cs)	56. Barium (Ba)	57. Lanthanum (La) 58. Cerium (Ce) 59. Praseodymium (Pr) 60. Neodymium (Nd) 61. Illinium 62 Samarium (Sa) 63. Europium (Eu) 64. Gadolinium (Gd) 65. Terbium (Tb) 66 Dysprosium (Ds) 67. Holmium (Ho) 68. Erbium (Er) 69 Thulium (Tu) 70. Ytterbium (Yb) 71 Lutecium (Lu)	72. Hafnium (Hf)
Period IX	79. Gold (Au)	80 Mercury (Hg)	81 Thallium (Tl)	82 Lead (Pb)
Period X	87.	88. Radium (Ra)	89 Actinium (Ac)	90. Thorium (Th)

FAMILY GROUPS

Group 5.	Group 6.	Group 7.	Group 8.
			2. Helium (He)
7. Nitrogen (N)	8. Oxygen (O)	9. Fluorine (F)	10. Neon (Ne)
15. Phosphorus (P)	16. Sulphur (S)	17. Chlorine (Cl)	18. Argon (A)
23. Vanadium (V)	24. Chromium (Cr)	25. Manganese (Mn)	26. Iron (Fe) 27. Cobalt (Co) 28. Nickel (Ni)
33. Arsenic (As)	34. Selenium (Se)	35. Bromine (Br)	36. Krypton (Kr)
41. Niobium (Nb)	42. Molybdenum (Mo)	43. Masurium (Ma)	44. Ruthenium (Ru) 45. Rhodium (Rh) 46. Palladium (Pd)
51. Antimony (Sb)	52. Tellurium (Te)	53. Iodine (I)	54. Xenon (X)
73. Tantalum (Ta)	74. Tungsten (W)	75. Rhenium (Re)	76. Osmium (Os) 77 Iridium (Ir) 78. Platinum (Pt)
83 Bismuth (Bi)	84. Polonium (Po)	85.	86. Niton (Nt)
91. Protoactinium (Pa)	92. Uranium (U)		

actually exists (see Table). The elements have been placed in order, and each one has a number called its atomic number.

In their chemical properties there is a strong family likeness between all the elements in Group 1, and the same is true of Groups 2, 3, 4, 5, 6, and 7. As in human families, some members resemble each other more than others. The closest resemblances are those between, in Group 1, lithium, sodium, potassium, rubidium, and cæsium; in Group 2 between calcium, strontium, and barium; in Group 3 between the rare-earth elements; in Group 5 between nitrogen, phosphorus, arsenic, antimony, and bismuth; in Group 6 between sulphur, selenium, and tellurium, and in Group 7 between fluorine, chlorine, bromine, and iodine. Group 8 is a curious sort of group; of the elements contained in it helium, neon, argon, krypton, xenon, and niton resemble each other very closely, but they do not resemble the other elements in the group at all; iron, cobalt, and nickel resemble each other very closely, so do ruthenium, rhodium, and palladium, and so do osmium, iridium, and platinum.

There is one characteristic that applies to all the groups except Group 8. The elements in the same group have, in general, the same valency or combining power. Those in Group 1 are monovalent, in Group 2 divalent, and so on. Valency is not, however, a definite, unalterable quantity. Moreover, some of the elements with small atomic weights have a valency less than we might expect; thus oxygen never has a valency of six; it is usually divalent, but is sometimes tetravalent, combining with four other groups, or groups and elements. Fluorine is always or nearly always monovalent, it is never heptavalent; all the same, the compounds of fluorine—the fluorides—closely resemble the chlorides and in the chlorides sodium is monovalent. In other compounds—for instance, the perchlorates—

chlorine is heptavalent, as manganese is in the permanganates.

Iron, cobalt, and nickel can be either divalent or trivalent; osmium, in Group 8, is the only element that is octavalent, and osmium is not always octavalent.

The chemical properties of the elements, of which valency is the most significant, gradually change from lithium to fluorine, and from sodium to chlorine, until some sort of maximum is reached, and then the cycle begins over again. The same thing is true of other properties of the elements—for instance the temperatures at which they boil or melt, the size of the atom of the element, and so on.

The order of the elements in the Periodic Table is very nearly the same as the order obtained if we arrange the elements in the order of their atomic weights, but there are two or three exceptions which long puzzled chemists. Argon has an atomic weight of 40 and potassium one of 39, but argon precedes potassium in the table. There is, however, no doubt that argon should be placed in the same group as helium and neon, and potassium in the same group as lithium and sodium. Another exception is that of the elements tellurium (atomic weight 127·5) and iodine (at. wt. 126·9); in this case also there is no question; tellurium closely resembles selenium, and must be placed in Group 6, whilst iodine in all its chemical qualities resembles bromine and must undoubtedly be placed in Group 7. The atomic weights, although interesting, are not of such importance as some other chemical qualities; we shall find later how little does the atomic weight determine the nature of the element. The chemical nature of the element really depends upon factors which do not affect the weight of the atom to an appreciable extent.

The circumstance that iron, cobalt, and nickel are entirely different from helium and the other rare gases upsets the regularity of the table, and in exactly the same way the fact that ruthenium, rhodium, and palladium do not resemble the rare gases introduces another irregularity. This irregularity is well seen if we show on a chart the boiling point or the volume of the atom of each element, taken in their order of the periodic table.

The diagram (pages 56 and 57) shows the relative volumes of the atom of most of the elements. In the case of solid elements these can be obtained by dividing the atomic weight by the density. In most of the rare gases the atomic volumes are deduced from data obtained from the density of the liquefied gases. The volumes of the atoms of nitrogen, oxygen, and fluorine have been calculated from the atomic radii as given by Bragg.

The atomic volumes of hydrogen and helium have been omitted from the table, as the data seem not to be comparable with the others.

It will be noticed that in some cases two different figures have been given for the volume of the atom of an element. The diamond and graphite have different densities and different atomic volumes, although both of these substances are varieties of the same element carbon. There are different varieties of tin with different atomic volumes, and different varieties of phosphorus and selenium. Such different varieties are discussed later, but the explanation is shortly that the atom is not a solid, incompressible particle. It is compressible, and can be squeezed together or allowed to expand in accordance with the degree of attraction between it and the neighbouring atoms. This is true of atoms in general, not merely those of the four elements we have mentioned; we have not shown in the diagram all the known variations in atomic volume; we have merely picked out a few glaring examples. Had we inserted all these, the general character of the table would have remained, but it would have been confusing and difficult to draw and to understand.

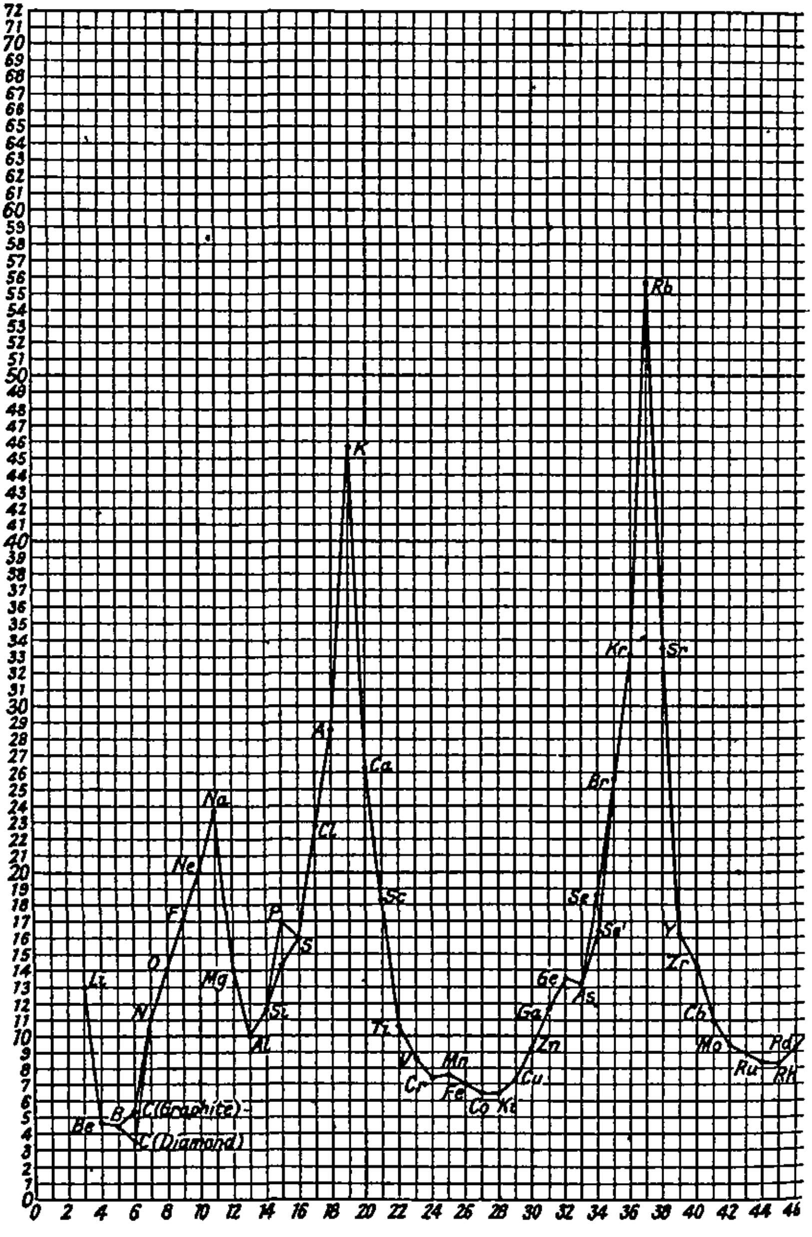
It will be noticed that the elements fall into three short groups, two long groups, and one very long group which is enlarged by including the remarkable rare-earth elements. It is impossible to give an account of these anomalies without considering something of the structure of the atom, a branch of knowledge that was quite beyond our reach in the days of Mendeléeff. By a study of X-rays, the solar spectrum, and the spectra emitted by many elements, and by other means we now know enough to explain far more.

It happens that a study of atomic weights affords a very interesting clue to the nature of atoms. If we plot *on a chart the atomic weights of the elements we obtain* the following diagram (page 58) which was first prepared in the year 1918. It is sufficient for our purpose to take the first 24 elements and to assume that the same general deductions, with occasional modifications, will apply to the whole long list of elements, 92 in number.

The atomic weights all fall on a series of parallel lines, and if we denote the atomic number by the letter x and the atomic weight by y, we find that the atomic weights of helium, carbon, nitrogen, oxygen, neon, magnesium, silicon, sulphur, and calcium all fulfil the following condition, $y = 2x$.

In the case of the elements lithium, beryllium, boron, fluorine, aluminium, phosphorus, and potassium the relationship between y, the atomic weight, and x, the atomic number, is expressed by the relationship $y = 2x + 1$. In the case of argon, titanium, and chromium the relationship is $y = 2x + 4$.

Every step forward along any one of these lines means an addition of 2 to the atomic weight, or approximately 2. The element chlorine with an atomic weight of 35·45 is an exception. It will be found in the case of the elements with higher atomic numbers and atomic weights that in


0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46
Li
Be
B
C(Graphite)
C(Diamond)
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
A
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
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Se'
Br
Kr
Rb
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Zr
Cb
Mo
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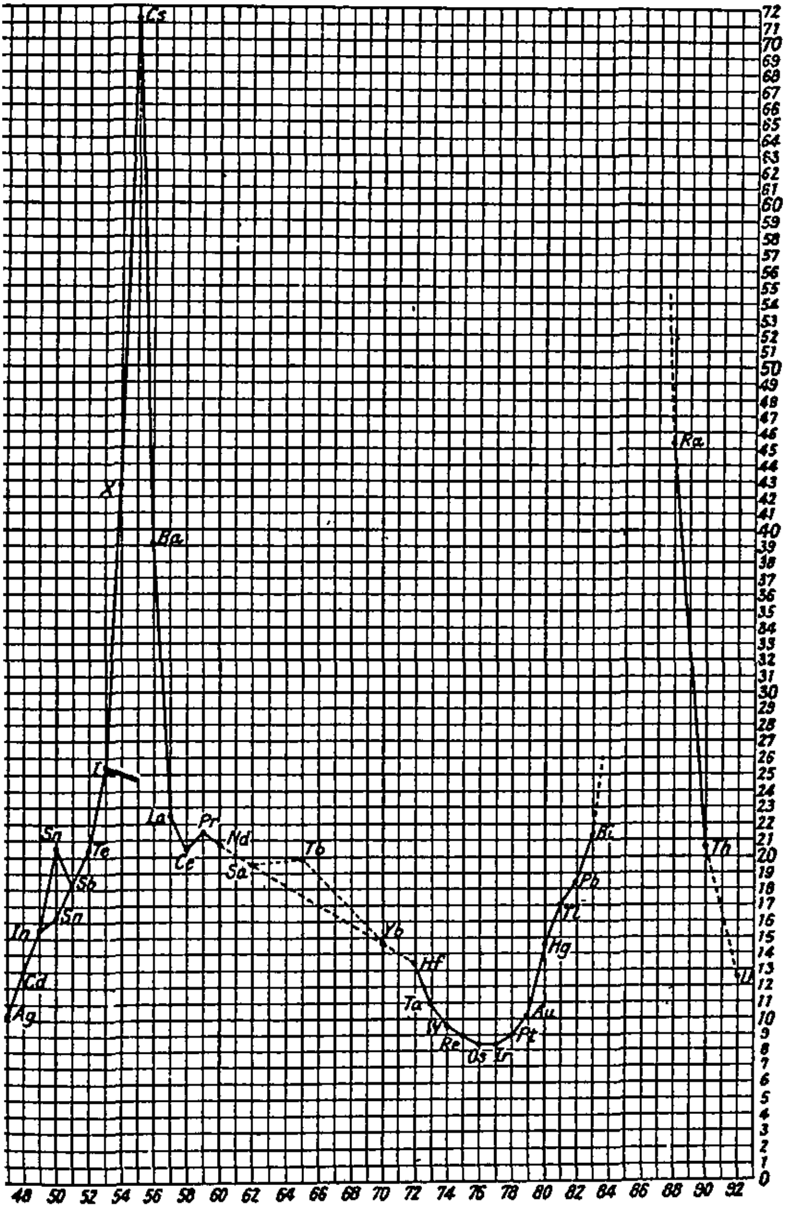
Rh
Pd


Cs
X
Ba
Ra
I
La
Pr
Nd
Sn
Te
Tb
Th
Ce
Sa
Bi
Sb
Pb
Sn
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Yb
Hg
Hf
Cd
U
Ta
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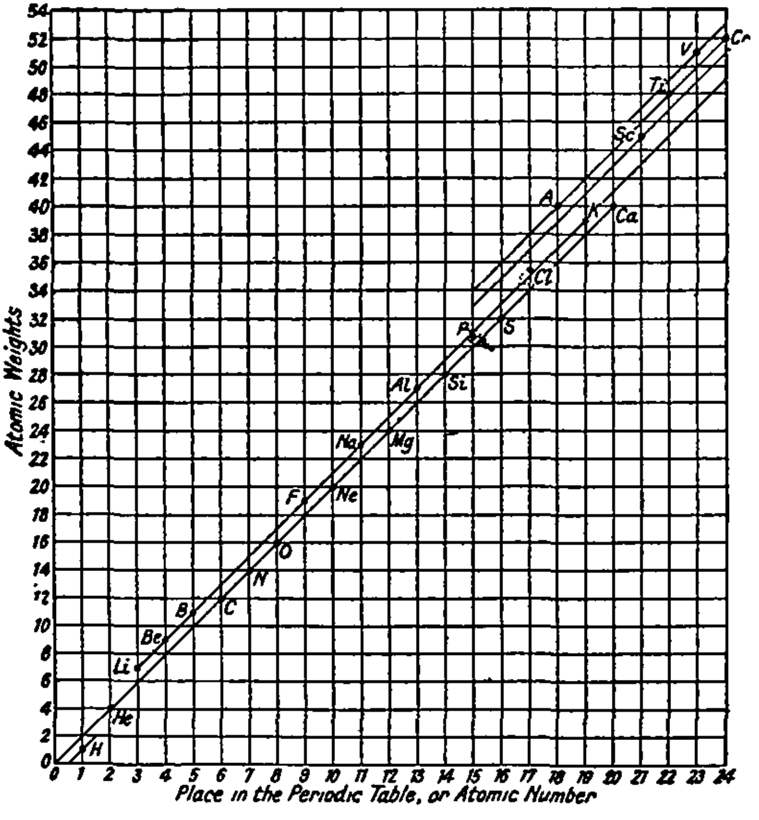
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72
48 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92


Atomic Weights
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
54
0
1
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5
6
7
8
9
10
11
12
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15
16
17
18
19
20
21
22
23
24
Place in the Periodic Table, or Atomic Number
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
A
K
Ca
Sc
Ti
V
Cr

no case is the atomic weight less than twice the atomic number, and in many cases the atomic weight exceeds twice the atomic number by 8 or 10 or 15 units or more. But we have only to look at carbon, nitrogen, and oxygen on the diagram and close to them, lithium, beryllium, and boron, to see that the normal and usual thing is to find a change of 2 units in the atomic weight for each change of 1 unit in the atomic number.

Let us consider argon and potassium for a moment; the atomic weight of argon is on a different line from that of potassium. We may say that had the atomic weight of argon been on the same line as that of potassium, the atomic weight would have been 37, instead of 40. What is the reason for this increase of 3 in the atomic weight of argon? The explanation is that the general chemical properties of an element depend upon its place in the periodic table for all the elements in this diagram and a great many others, but the atomic weights depend not only on the part denoted by $2x$ (which usually determines the chemical properties), but also on the odd 1, or 3, or 4 units that contribute to the atomic weight. These odd units contribute to the weight of the atom without affecting its chemical properties. Potassium has 1 unit in its atomic weight that has no effect on its chemical properties; argon has 4 units that have no effect on its chemical properties. They neither cause its chemical inertness nor modify it.

With the exception of hydrogen, helium, carbon, oxygen, neon, magnesium, silicon, sulphur, and calcium, every single element contains in its atom some matter that has weight and has no effect on its chemical nature. In some cases it has been possible to obtain two or more varieties of a chemical element with different atomic weights and identical chemical properties. Chlorine is such an element; there are two varieties of it, one with the atomic weight 35, the other with the atomic weight 37, and it is impossible chemically to distinguish between the two. Ordinary chlorine is a mixture of these two containing about three times as much of the former as of the latter variety. It is impossible by any chemical means to separate the two. It is because ordinary chlorine is this mixture that it has the atomic weight of 35·45 and does not fall into line with many of the other elements.

The atomic number of chlorine is 17, and twice this is 34; we can easily see that the lighter variety of chlorine has in its atom one unit that is chemically inert and does not affect its chemical nature; the heavier variety of chlorine has three such units. This is not the time to pursue this matter much further; the structure of atoms is a fascinating study, but it comes later in the story. Meanwhile it is proper to point out that we have at last an explanation of the fact that argon has a higher atomic weight than potassium, but a lower atomic number, and a similar explanation can be given of the exceptional order of the elements tellurium and iodine.

When we consider the elements iron, cobalt, and nickel, which have very similar chemical properties and are placed in the same division in the periodic table in Group 8, we must apply the same sort of explanation, and this prevails also in the group of rare-earth elements from lanthanum to lutecium inclusive. Their chemical properties are extraordinarily similar; the portions of their atoms that are chemically active are nearly the same, but they contain different amounts of matter that affect the atomic weight and not the chemical properties. This is rather a crude way of stating the fact, and is not a satisfactory explanation, but it is sufficiently near to the truth to answer our purpose at the moment. The family groups suggest that one element differs from another that is one step lower in the periodic table by the addition of a unit of 2 in the atomic weight, which in some way is connected with the chemical properties and by a variation sometimes in the amount of inactive or inert matter contained in the atom.

It appears that the valency of an element, which is extremely closely connected with all its chemical properties, steadily increases from 1 to 2, 3, 4, and so on, until it attains a maximum of seven or even eight, and that then it begins again, there being a stage, often but not always, when at this turning point there is an element with no chemical activity whatever. The arrangement of the elements in this curious way is certainly not simple and it cannot be made simple; it is, however, an arrangement that is in accordance with the facts, and we must leave it at that. We shall show in later chapters that the details of the table are supported by evidence obtained from an examination of chemical compounds by means of the spectroscope, and also by evidence obtained by observing the effect of *X*-rays on chemical substances.

CHAPTER V

ELECTRICITY AND CHEMISTRY

THE most astounding discovery during the last two hundred years is probably the discovery that electricity is present in every solid, liquid, and gas, and that it is electricity that binds together the ninety-odd chemical elements so as to form the hundreds of thousands of chemical compounds. Electricity is at the bottom of every chemical change and every chemical manufacture. All chemical change involves a transference of units of electricity from one position to another, and this chapter is devoted to some of the elementary parts of the explanation of this fact.

When we look back for a period of a hundred or a hundred and fifty years, we can see which of the early pioneers pursued a path that led to the truth, and which pursued paths that led them merely into a maze or a blind alley, and here we have the advantage over the early pioneers. They were to some extent fumbling about in the dark, and many of them, whose names are almost forgotten, made a few steps on what ultimately turned out to be a main road to the truth.

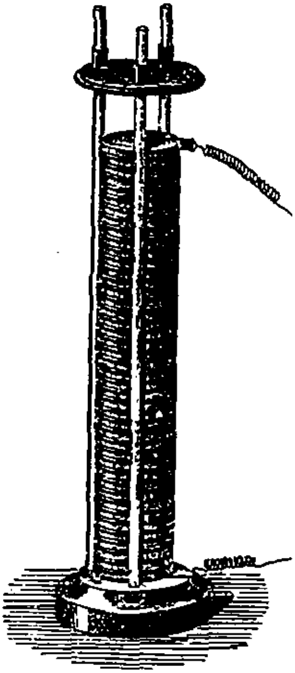
If we regard Lavoisier and Dalton as outstanding in the field of the theory of chemistry, we must remember that such men as Berzelius, Wollaston, Gay-Lussac, and Dumas did a great deal to make analyses more accurate, to prepare new compounds, and provide much material for their successors to explain. Moreover, entirely new methods became available for investigating the nature of chemical combination and finding how compounds are put together.

It has long been known that electricity can be used to break up a chemical compound so that one or more of its elements may be obtained. In the very early days, when friction machines were the only practical sources of electricity, they were used to supply a current of electricity, and in 1789 van Troostwijk and Diemann decomposed water by electricity from a frictional machine. The discoveries of Galvani and Volta enabled a much more convenient source of electricity to be used.

Luigi Galvani was a physician of Bologna, who published a paper in 1791 describing some experiments in which a leg of a dead frog was brought into contact first with a steel scalpel and afterwards with two different metals. An electric current was set up sufficient to induce a muscular contraction. Shortly afterwards Alessandro Volta, professor of physics in Pavia, described a number of experiments he had made in which different metals were brought into contact with each other in a nearly dry state, or when they were separated by a moist conductor; he pointed out that in these circumstances one metal always showed a positive electric charge and the other a negative charge, and he published a list of substances in such an order that each was electrically positive to all the substances that followed it. He used at one time a plate of silver and another of zinc, separated by a layer of cloth or cardboard dipped in water or a salt solution; afterwards he used several pairs of such metal plates, and finally a pile of discs of copper and zinc separated by moist discs of cloth or cardboard, as shown in the illustration.

Afterwards Volta made a "crown of cups," each cup containing a plate of copper and one of zinc immersed in water containing a little acid. Each pair of plates gave a current of about one volt, so that it was easy, by using enough plates, to obtain a current of ten or twenty volts —ample for many of the early chemical experiments.

Volta described his "pile" in a letter to Sir Joseph Banks, then President of the Royal Society, in March 1800. In May of that year water was decomposed by a Voltaic pile by William Nicholson and Alexander (afterwards Sir Alexander) Carlisle, who were surprised to find that the oxygen came off at the positive pole and the hydrogen at the negative pole, instead of coming off mixed together.



With a Voltaic pile Humphry Davy was able in 1807 and 1808 to decompose caustic soda, caustic potash, lime, baryta, and strontia, and so isolate for the first time the metals sodium, potassium, calcium, barium, and strontium. Davy was born in Penzance in 1778, the son of Robert Davy, a wood-carver and small farmer. In 1795 he was apprenticed to a Penzance surgeon and apothecary; his work led him naturally to chemical experiments and speculations, and in 1798 he was appointed superintendent of a Pneumatic Institution at Bristol to investigate the medicinal effects of gases. Here he made his name by his investigation on the physiological effects of nitrous oxide —"laughing gas"—then a fashionable plaything. In 1801 he came to London as Lecturer at the Royal Institution, and in the following year he was made Professor. Davy's lectures were very popular and extremely fashionable. He was knighted in 1812, and later made a baronet for his services to chemistry. In addition to his isolation of the metals we have mentioned, Davy is famous for showing that chlorine is an element and for his invention of the miners' safety-lamp, named after him, that has been the means of saving so many lives. He died in 1829, at the age of fifty.

When you decompose water by an electric current the two elements oxygen and hydrogen appear at different points in the electric circuit, one at the positive pole and one at the negative, and the Swedish chemist Berzelius built up a rather elaborate doctrine of electro-positive and electro-negative elements that were mutually attractive. There is a germ of truth in this doctrine, but Berzelius tried to make it explain far too much, and he had great arguments with Dumas and others that need not detain us here.

It was Faraday who did most, rather more than a hundred years ago, to put all those who came after him on to the true path that has led to the telephone, and the wireless, and to the electron, as well as such simpler things as nickel plating and chromium plating; Faraday in 1831 discovered the induction coil that led to the dynamo, and without this we should not now enjoy the luxuries of electric light, telephohes, and electric stoves in our houses. In 1833 he discovered the laws of electrolysis (breaking up compounds by electricity) and established the electrolytic methods on a scientific footing, so making it possible for us now to have pure zinc, and cheap aluminium, and cheap hydrogen, and cheap chlorine for keeping our swimming-baths sterile, and a host of other things. We owe much to Faraday, the son of a poor blacksmith; this great discoverer was born in London in 1791, and had a very imperfect education, and began to earn his living as a newspaper boy at the age of thirteen, but he had brains and industry, skill and genius. In 1813 he was appointed Davy's assistant at the Royal Institution and he ultimately succeeded Davy there. The characters of the two men were very different; while Davy loved admiration and his fashionable position, Faraday was of a more modest, simple nature, was deeply religious, and beloved by all with whom he came in contact. His lectures were as popular as Davy's had been. He died in 1867, after having done as much for science as probably any other Englishman, either before or since. While he did so much to enlarge our knowledge of the theory of electricity, other workers did much to apply electricity to the service of mankind. Instead of the primitive cells of Volta, a much better battery with a nearly constant current was invented by Daniell in 1836, and in that year the Elkingtons began electroplating in Birmingham; nickel-plating was discovered in 1842, but did not become commercially useful until many years later.

That there was some connexion between chemical combination and electricity was obvious in the days of Berzelius and Faraday, but exactly what the connexion was could not be explained until much later. We can easily see that electricity can produce chemical change; the electrolytic decomposition of water is an example of this. We also realize that chemical change can produce electricity; the batteries of Volta and Daniell are proof of this. In 1859 Planté invented a lead accumulator that can be used for the production of an electric current by the action of sulphuric acid on lead and lead compounds. On the other hand, if you pass an electric current through the accumulator when it has run down, various chemical changes are effected which bring the chemical compounds into a state in which they will again generate electricity. It has been improved since that time, but is still in use in millions of motor-cars and wireless apparatus. Accumulators consist of a number of plates of lead, and each alternate plate is connected to one wire, and the remaining plates are connected to another wire. The plates are covered with a mixture of oxides of lead and sulphate of lead, and are placed in dilute sulphuric acid. By means of a dynamo or some other electrical device a current is passed from one set of plates to the other. While the current passes, lead peroxide is formed on one set of plates and metallic lead on the other set of plates, and a little extra sulphuric acid is made. When the current is switched off and the accumulator is allowed to generate electricity, the sulphuric acid acts on the lead, the lead oxide, and peroxide, to form sulphate of lead and water, and a current of electricity flows until the plates and the acid attain a state of equilibrium. Then the dynamo may be connected up again and the process repeated almost indefinitely. As the sulphuric acid is used up, the density of the liquid decreases, and by reading the density with a hydrometer it can be determined whether the accumulator is fully charged, or half charged, or uncharged. Some wireless accumulators have little balls that float or sink according to the density of the liquid, and hence show the state of charge of the battery.

Electricity is composed of small units or particles of electricity, to which the name electron was given by Johnstone Stoney. These particles of electricity are shot out at a high speed from the cathode or negative pole in the sealed glass tubes, in which there is almost a vacuum, called Crookes's tubes, and we owe to Sir J. J. Thomson of Cambridge the discovery, made in 1897, that the cathode rays consist of a stream of particles, units of electricity, electrons flying at high speeds.

To give a proper account of the many important processes in which electricity is used in the manufacture of chemicals would need a whole book, not merely a part of a chapter. But as we are concerned with the main principles involved, and not the industrial details, we shall give only a brief explanation; the reader who wishes to learn this subject should consult the text-books that deal with it specially.

Electricity is used for different purposes in the chemical industry—for instance the preparation of a metal from a molten compound of the metal, the purification of a metal by dissolving the impure metal in an acid, and then depositing the metal in a pure state by electrolysis; the deposition of a coating of one metal upon another, and the conversion of one chemical compound into another.

If a current of electricity is passed through a solution of impure copper sulphate, using an impure copper rod as an anode or *positive* pole, the *impure copper will dissolve* and nearly pure copper will be deposited at the cathode—that is to say, a metal containing about 99·93 per cent. of copper, the muddy deposit left in the bottom of the electrolytic cell will contain a small amount of copper, but nearly all the silver, gold, selenium, tellurium, antimony, arsenic, bismuth, and other elements that it was thought desirable to remove from the impure copper, either because they were injurious to the copper or were too valuable to be sold as copper.

In a similar way, gold, nickel, or cadmium may be electrically deposited in a pure state by passing a current through a fused salt of the metal.

Electroplating is usually carried out by passing a current through a solution of a metallic salt in water; for silver plating a solution of a mixture of silver cyanide and potassium cyanide is commonly used and silver is transferred from a pure silver anode and plated on to the required object, which is used as the cathode; for nickel plating a mixed solution of nickel ammonium sulphate, $NiSO_4(NH_4)_2SO_4$, and nickel sulphate, $NiSO_4$, is used, and the nickel is similarly plated by transference through the solution. Similar methods are used for the recent chromium plating and the still more recent rhodium plating.

It is not only possible to deposit a hard uniform layer of a metal; in some cases it is possible to deposit a hard uniform layer of an alloy; thus if a current is passed through a mixed solution of the cyanide of potassium and zinc, $K_2Zn(CN)_4$, and the cyanide of potassium and copper, $KCu(CN)_2$, a very good deposit of brass may be obtained. Brass plating is now extensively practised in industry.

Electrolytic methods are not confined to such metals as silver, copper, nickel, and chromium. If a current is sent through a solution of common salt, NaCl, in water, the sodium chloride is split up, the sodium being produced at the cathode and the chlorine at the anode. But as fast as the sodium is produced at the cathode it acts on the water, as sodium always does, forming caustic soda and hydrogen thus:

$$\underset{\text{sodium.}}{Na} + \underset{\text{water.}}{HOH} = \underset{\text{hydrogen.}}{H} + \underset{\text{caustic soda.}}{NaOH}$$

The actual products of the electrolysis are therefore hydrogen and caustic soda at the cathode and chlorine at the anode. If the chlorine is allowed to combine with the caustic soda, sodium hypochlorite is formed, and by altering the methods employed, chlorate of soda may be obtained.

The chlorate of potash, $KClO_3$, so well known as a mild drug, is made on a large scale by a similar process.

Hydrogen, oxygen, white lead, bromine, magnesium, calcium, sodium, aluminium, and cerium can now be made electrolytically, and so can many other common substances. The purple crystals of potassium permanganate are fairly familiar, and they are prepared by an electrolytic process. An impure manganese dioxide, MnO_2, is roasted with caustic potash, KOH, in the presence of air, so making an impure potassium manganate, thus:

$$MnO_2 + 2KOH + O = K_2MnO_4 + H_2O$$

The manganate is dissolved and a current passed through it, when the following action takes place:

$$2K_2MnO_4 + 2H_2O = \underset{\text{potassium permanganate.}}{2KMnO_4} + 2KOH + H_2$$

The potassium permanganate is allowed to crystallize out; the caustic potash is recovered, and used over and over again to form potassium manganate.

These are, no doubt, sufficient examples to show how important an agent electricity is in the production of chemical change. Indeed, the connexion between electricity and chemistry is closer than we have indicated.

It is not at all easy to explain the nature of electricity; just as the smallest unit of sulphur is the atom of sulphur, so the smallest unit of electricity is the electron. If we could cut the sulphur atom into halves, the half would not be sulphur, but something else; if we could cut the electron into bits, the bits would not be electricity. The electron behaves as a particle; it has a definite position and a definite but very small weight. It also behaves like a wave or vibration travelling through space at an incredible speed. If we are surprised that the electron can behave partly like a vibration, comparable with light, and partly as a speck of matter, our surprise is due to the fact that we are not accustomed to the habits of specks of matter, but only to huge lumps of matter, lumps many thousands times as big as an electron. The little specks of electrons hold grosser matter together as the thin layers of mortar hold together the solid bricks in a wall. We must not judge the nature of the mortar from the nature of the wall.

The human mind has been accustomed to form mental pictures resembling the pictures we see with our eyes, and it is almost impossible for us to comprehend that there are things that may be regarded as intermediate between matter and energy. But it does not follow because we cannot form a mental picture of them that such intermediate bodies do not actually exist.

When we look at matter in quantity, we have one set of ideas; when we consider it minutely, we find that there is no sharp distinction between solid matter and empty space, between mass and energy, between solid particles and immaterial vibrations. A brick consists perhaps of 99 per cent. of empty space and 1 per cent. of solid matter, depending on how you define empty space. What we ordinary people regard as empty space contains rather a greater proportion of it than a brick does; that is all the difference.

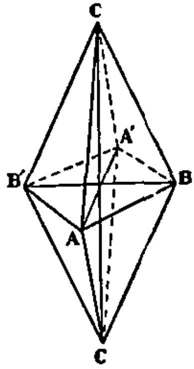
CHAPTER VI

CRYSTALS AND THE ARRANGEMENT OF ATOMS IN SPACE

IT is very easy to grow crystals of some particular substances; copper sulphate is an easy one to begin with. If you buy from a chemist's shop a quarter of a pound of copper sulphate in lumps, you will find that it is a mass of broken or imperfect blue crystals. Take a dish, two or three inches deep, and fill it more than half full of water, then put in some copper sulphate lumps and broken pieces of crystals and wait until these have dissolved; go on adding more solid copper sulphate until no more will dissolve in the liquid; leave it for an hour or so to make quite sure that you have dissolved all that is possible, and then pour off into another dish the clear solution, which is blue in colour, and leave it, preferably in a place where the temperature does not alter very much; a cellar does very well. After some hours you will find several small crystals have deposited themselves in the liquid because some of the water has evaporated. Collect all these crystals and put back into the liquid about half-a-dozen of them. In a few more hours they will have grown in size. If you remove all the small crystals as they form, and keep the half-a-dozen you wish to grow, you can in a few days obtain nice large crystals as big as an almond or bigger.

The growth of a crystal resembles in some ways the growth of a plant, but it differs in many very important ways. The growth of a crystal of copper sulphate takes place so as to form a particular shape, because the different atoms that form the copper sulphate crystals naturally attract each other into some special arrangement that depends on the number and the respective sizes of the various atoms. The growth is caused by the formation of one substance only—the formation, from the solution, of the matter of which the crystals are formed. So long as the conditions are favourable—that is, so long as water is slowly evaporating from the solution—the crystals will continue to grow in their ordained way.

If we look casually at a collection of crystals there seems to be an almost infinite variety of them, but a careful examination shows that they may be divided into seven classes, depending on what are called the axes of the crystals. It we take a simple crystal of this nature and draw lines connecting the opposite angles *AA′*, *BB′*, and *CC′*, we get three axes and the length of these axes and their positions determine the whole structure of the crystal. In the first system—the cubic system—all the axes are of equal length and all at right angles to each other. Common salt, fluorspar, and iron pyrites crystallize in this system. In the second, or tetragonal, system the axes are all at right angles, but only two are of equal length. In the third system, the orthorhombic, all the axes are at right angles and no two are of the same length. In the fourth or monoclinic system all the axes are of different lengths, two are at right angles with the third, the other axes are not at right angles with each other. In the fifth or triclinic system all the axes are of unequal length and no two are at right angles with each other. Copper sulphate crystallises in this system. The sixth or trigonal system has all its axes of equal length and at equal angles with each other, but not at right angles. Calcite, or Iceland spar, crystallizes in this system, and so does quartz. The last system—the hexagonal—has four axes and not three; three of the axes are equal to each

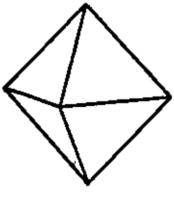


other and lie in the same plane at equal angles; the fourth axis is at right angles to the other three.

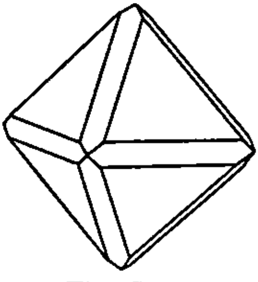
Once the axes of a crystal are known we can predict all the possible faces of the crystal that can occur. No substances display all the possible faces, but many substances will display a great many; the small crystals of copper sulphate usually display six faces; the large crystals may display sixteen or more.

The brilliant colours of many crystals and the way they refract light and reflect it make a collection of them an exhibition of extraordinary beauty; it is easy to grow small ones, but to grow large ones requires a great deal of patience.

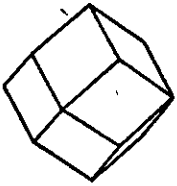
The definite shapes of crystals depend on the number, the sizes, and the arrangement of the molecules or atoms of which they are composed. There is not an infinite number of ways in which you can arrange a number of atoms in a regular order in space; there are seven great classes of these, and each class is represented by many crystalline forms. Some of these forms are related to each other in a very simple manner, so that the same substance will normally crystallize in two or more closely related forms. If we take as an example a simple crystal such as a regular octahedron, we find that it is quite easy to split off the edges of the different faces with a knife, because there is a natural plane of cleavage. If this operation is carried out on all the edges, we shall get such a crystal as this:



Octahedron.



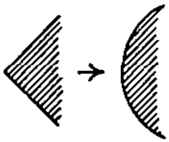
First Stage.



Final Stage.
Dodecahedron.

and if we continue the operation until all the triangular faces are cut away, we shall eventually obtain a rhombic dodecahedron as shown in the illustration. The reason why such a plane of cleavage exists is this: there is a regular layer of atoms on this plane, and at very minute intervals above and below it there are other layers parallel to this. Not only can we artificially cut off the edge in the way we have mentioned, but there is very often a tendency for such a cutting off to take place naturally as the crystal grows.

If an octahedron of alum is suspended in a saturated solution of alum, the crystal will neither grow nor dissolve so long as the temperature remains the same and no evaporation of water takes place (see Plate III, p. 90). If water evaporates, the crystal will grow pretty regularly on all its faces. If the temperature rises, the crystal will diminish in size, because alum is more soluble in hot water than in cold. Now, when a crystal diminishes—or dissolves, in other words—the greatest diminution takes place at the edges, because these are exposed to a greater surface of liquid than the faces. The edges will become blunted thus:



and if the temperature falls and the crystal begins to grow again, it is quite likely that a new face will appear instead of the old edge; we shall get this:

If a crystal of a substance that is soluble in water, like alum or copper sulphate, is kept in a solution and allowed to grow, these new faces are apt to appear, because unless great precautions are taken the temperature will rise and fall slightly each day.

The same change will take place if the substance naturally crystallizes in cubes or in any other form. But such changes always take place in regular and definite ways, at definite angles that depend on the way in which the atoms are arranged in the crystal.

We can conceive of the crystal as being formed by the packing as closely as possible of spheres of different sizes representing the different atoms. The spheres of hydrogen will be of one size, those of oxygen rather larger, those of chlorine still larger, and it is possible, as was shown by Pope and Barlow in 1909 and 1910, to connect the shape of many crystals with their chemical composition. Pope and Barlow also discussed the different ways in which close packing can be achieved with spheres of uniform size or spheres of two different sizes. Since the date of this work the use of *X*-rays to determine the structure of crystals has been developed, and this enables the actual volumes of the spheres and their arrangement to be determined with greater certainty and accuracy. When we consider crystals as being built up of closely packed spheres, we must remember that the mass of the atom is really concentrated in a small particle at the centre of the sphere.

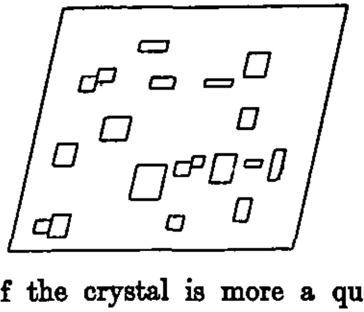
The surface of a solid—a crystal, for instance—is not to be regarded as the surface of a wall. It is to be regarded as a great empty space with a few small particles at regular distances from each other. We can compare such a surface with a flat, treeless piece of country in which in every ten acres there is a man with a machine gun and an abundance of ammunition. The country may be sparsely populated but you cannot penetrate far in it. All solids and all liquids have far more empty space than they have particles of heavy, solid matter. Gases contain a still greater proportion of empty space.

If we consider a concentrated solution of copper sulphate, ready to deposit crystals, we find that the various atoms of copper, sulphur, and oxygen in copper sulphate, $CuSO_4$, do not fill up the whole of the crystal shape; there is room left over, and this extra space is filled up, as much as is possible, by water, so that the blue crystals of copper sulphate, with which we are familiar, are of this composition, $CuSO_4,5H_2O$. Whether we regard this substance as a chemical compound or as a close-packed assembly of $CuSO_4$ and H_2O held together either by electrical attractions or by the necessity for filling up the space in the crystal with something, is a rather nice point. It depends on how we define a chemical compound, how we define space, what we mean by close packing, and such other considerations. The volume of the H_2O, or of the $5H_2O$, compared with the volume of $CuSO_4$, is, however, certainly a very important factor. The arrangement of atoms in a crystal must depend very largely on their size, and we find that molecules, or atoms arranged in a space lattice, if they contain the same number of atoms and the same volumes, often give crystals of the same shape, quite regardless of the chemical nature of the atoms concerned.

The various alums are a good instance of this. The common alums are crystals—we have no reason to believe they exist in solutions—represented by these formulæ:

$$K_2SO_4,Al_2(SO_4)_3,24H_2O$$
$$(NH_4)_2SO_4,Al_2(SO_4)_3,24H_2O$$

It is possible to form alums in which the potassium is replaced by the similar elements rubidium and cæsium; sometimes the potassium may be replaced by sodium or thallium: we may also replace the aluminium by chromium, iron, cobalt, nickel, or manganese, which give sulphates $Cr_2(SO_4)_3$, $Fe_2(SO_4)_3$, and so on, but we may also replace the K_2SO_4 by such very different substances as potassium beryllium fluoride, K_2BeF_4, and potassium zinc chloride, K_2ZnCl_4, and it appears from this that the volumes of K_2BeF_4 and K_2ZnCl_4 must be nearly the same as the volume of K_2SO_4. So, too, although their chemical properties are very different, we find that sodium nitrate, $NaNO_3$, and calcium carbonate, $CaCO_3$, crystallise in very similar shapes, and this is possible only because the volume of the sodium atom is about the same as the volume of the calcium atom, and the volume of the NO_3 group is very nearly that of the CO_3 group. The crystals of sodium nitrate resemble those of calcite, $CaCO_3$, so much that if a crystal of calcite is left in a saturated solution of sodium nitrate, small crystals of sodium nitrate will grow on the faces of the calcite, all in regular order with the edges of the small crystals of sodium nitrate parallel with the edges of the large crystal of calcite as in this diagram, almost as if they were parts of the original crystal.



The shape of the crystal is more a question of solid geometry than of anything else. As all the alums have the same form, it is possible to take a crystal of chromium alum and put it in a concentrated solution of the ordinary potash alum, and the crystal will continue to grow round the original one. So it is possible to grow mixed crystals of certain compounds whose crystals have the same forms.

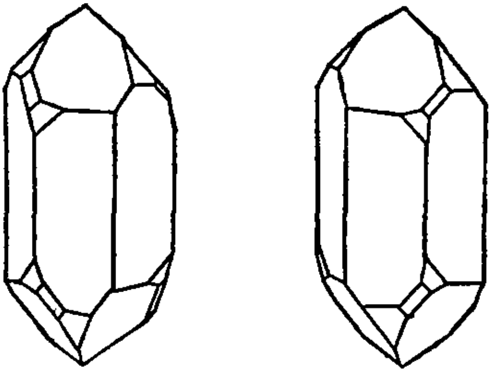
Mixed crystals and overgrowths of one crystal on another were studied by Romé de l'Isle in 1772, by Leblanc in 1784, and by many subsequent observers.

On pages 56 and 57 there is shown a diagram of the atomic volumes of the various elements, and we shall find, if we study this carefully, that some elements not only have the same valency, but also very nearly the same size of atoms. In such cases we must expect these elements to resemble each other very closely and their respective compounds to do the same. Zirconium and hafnium form a pair of such elements; niobium and tantalum form another such pair.

Crystals are usually transparent, and it sometimes happens that when rays of light traverse a crystal they become polarized. Light rays consist of vibrations in all directions, and polarization means that, in passing through the solid crystal, the vibrations all emerge vibrating in one special direction. The direction in which they lie can be determined by an instrument called a polarimeter.

When polarized light travels through certain crystals or solutions, the direction of the polarization is changed, and one sort of crystal that has this effect is the common rock-crystal or quartz. Arago, a Frenchman, noticed this in 1811, and his compatriot Biot noticed in 1812 that some crystals of quartz rotated the polarized light in one direction and other crystals of quartz rotated it in the other direction. The power possessed by some solutions and some crystals of changing the direction of polarized light is called optical activity, and it is one of considerable commercial as well as theoretical importance.

About the year 1815 the Abbé Haüy noticed that quartz crystals frequently have small faces on them at the corners of larger faces, and that sometimes these small faces appear at the right side of the large face, sometimes on the left side, as in this figure. Herschel in 1820 showed that a crystal of the type of figure *A* altered the direction of polarized light to the right, and that a crystal of the type of figure *B* altered the direction of polarization to the left.



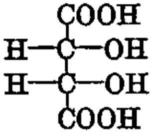
Quartz Crystals.

We have already pointed out that compounds exist having the same number of atoms of the same elements but possessing different properties. An instance of this came before the French chemist Pasteur in 1848, and led that great genius to make some remarkable discoveries. Tartaric acid and several of the tartrates were well known in the early years of the nineteenth century, and in 1815 Biot noticed that crystals of tartaric acid and solutions of tartaric acid were optically active; this is true also of many of the tartrates.

About the year 1821, Kestner, a chemical manufacturer of Mulhouse, discovered a new variety of tartaric acid, that had the same chemical composition as the old variety but different physical properties. The new variety is called racemic acid, and its crystals and its solution were found to have no optical activity. The compounds of racemic acid are called racemates, and many of these were prepared and crystals obtained from the solutions of racemates were examined. One racemate specially studied was the racemate of sodium and ammonium. The corresponding tartrate of sodium and ammonium had been known for more than a hundred years, and, like the tartrate of potassium and sodium (Seignette salt), was sold as a drug. Its crystals had been examined by crystallographers of repute, but Pasteur discovered some small faces on the crystals of sodium ammonium tartrate that had escaped the notice of the earlier workers. One day he took a solution of the comparatively new racemic acid and prepared from this a solution of the optically inactive sodium ammonium racemate. He set this solution aside, and as the water evaporated crystals began to form. When he had a sufficient quantity of these he examined them, and found, to his astonishment and delight, that half of the crystals were those of the ordinary sodium ammonium tartrate and the other half were precisely similar crystals, except that the small faces were placed in different positions from those in sodium ammonium tartrate. He separated the crystals into their separate kinds, and found that the new variety was optically active but in a direction contrary to the activity of the usual sodium ammonium tartrate. Not only had he prepared a new optically active tartrate, but he was able from this to prepare a new form of tartaric acid and a whole range of tartrates that differed from the old ones by being optically active in the opposite direction. He found that the so-called racemic acid solution behaved like a mixture of equal parts of solutions of the two tartaric acids, the right-handed and the left-handed. It is not perfectly certain to this day whether racemic acid exists in solution as an independent substance or as a mixture, but crystals of it can be obtained which are optically inactive, and although sodium ammonium racemate crystals do not separate at ordinary temperatures, they can be obtained at higher temperatures, and many racemates of other metals can be obtained in crystals. The most interesting thing was to find that, in addition to racemic acid, there were two kinds of tartaric acid, similar in every respect, except that one was right-handed and the other left-handed. Some years later a fourth variety of tartaric acid was found, that was optically inactive but differed from racemic acid. This is now called mesotartaric acid.

The only explanation of the existence of the two forms of optically active tartaric acid was that in one crystal the various atoms were arranged in a sort of spiral, so that the polarized light was made to twist as it travelled through the atoms, as a rifle-bullet is made to twist by the rifling of the barrel; in the other sort of crystal the atoms are also spirally arranged, but one of these spirals is a right-handed screw and the other a left-handed.

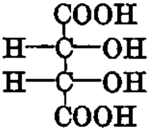
Tartaric acid has this structure :



$$\begin{array}{c} \mathrm{COOH} \\ | \\ \mathrm{H-C-OH} \\ | \\ \mathrm{H-C-OH} \\ | \\ \mathrm{COOH} \end{array}$$

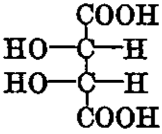
so far as structure can be represented on a flat surface like a sheet of paper, and although we cannot draw a screw-like arrangement of the atoms, we can produce three diagrams which in a crude way will illustrate the possibilities of optical activity and inactivity.

If we assume that the structure of 1 in the following diagram is optically active in a right-handed direction, 2 may be conceived as being optically active in a left-handed direction, and 3 as optically inactive.



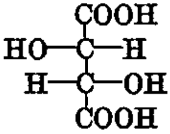
$$\begin{array}{c} \mathrm{COOH} \\ | \\ \mathrm{H-C-OH} \\ | \\ \mathrm{H-C-OH} \\ | \\ \mathrm{COOH} \end{array}$$

1



$$\begin{array}{c} \mathrm{COOH} \\ | \\ \mathrm{HO-C-H} \\ | \\ \mathrm{HO-C-H} \\ | \\ \mathrm{COOH} \end{array}$$

2.



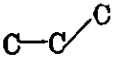
$$\begin{array}{c} \mathrm{COOH} \\ | \\ \mathrm{HO-C-H} \\ | \\ \mathrm{H-C-OH} \\ | \\ \mathrm{COOH} \end{array}$$

3.

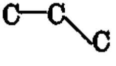
It is now clearly established that this is a good analogy; if 1 denotes right-handed tartaric acid, and 2 denotes left-handed tartaric acid, we consider 3 to be the new optically inactive mesotartaric form, and we consider crystals of racemic acid as an aggregate of the right-handed and left-handed tartaric acids. The solution of racemic acid will either be a compound of the right-handed and left-handed varieties or will be a mixture of them.

Pasteur found that he could only give a more exact explanation by guessing how the atoms are set out not in a diagram, but in space, and he thought that one explanation might be that the chemical attraction of carbon atoms in such a compound as tartaric acid is chiefly in four directions equally divided in space comparable with the directions that the corners of a tetrahedron make in relation to the centre. He made this suggestion rather vaguely, and did not pursue it, being attracted by research in other directions; but in the year 1874 two chemists, van 't Hoff and Le Bel, independently of each other developed this tetrahedral idea very successfully. It is now adopted by all chemists, and is extremely useful. The notion of a tetrahedral spacing of the attractions of the carbon atoms fits in very well indeed with the known facts of most carbon compounds, but it is not to be rigidly applied to all without exception.

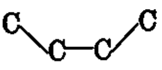
A tetrahedron has definite angles, and if we take these angles as defining the positions of the carbon atoms combined together, we shall find that three carbon atoms do not lie in a straight line, thus: C—C—C, but in two lines at the definite tetrahedral angle, thus:

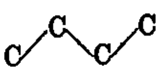


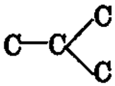
or



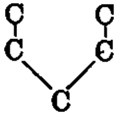
and four carbon atoms will similarly be joined together in one of these ways:



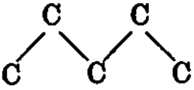




Five carbon atoms are usually joined together thus:

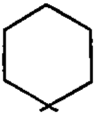


or

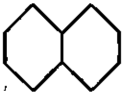


but other schemes are possible.

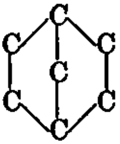
Five carbon atoms at tetrahedral angles may nearly form a complete ring; six carbon atoms at tetrahedral angles overlap a little, like this:



but in fact six carbon atoms form a symmetrical ring with angles that are not exactly those of a tetrahedron. A six-carbon atom ring can combine with one or two such rings, or with a four- or five-carbon ring. Naphthalene has a

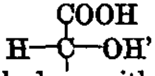


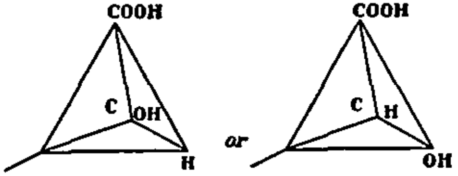
molecule that lies all in one plane; camphor contains two five-carbon rings thus:



These camphor rings are not both in the plane of the paper; the one ring will be inclined to the other at an angle rather more than a right angle. Many essential oils, of which turpentine is an example, contain compounds with such rings. Ruzicka, a Swiss chemist, has prepared compounds containing rings with 10, 12, 20, and 30 carbon atoms. Musk, the well-known scent, partly consists of a compound containing a ring of 15 carbon atoms.

The long chains of carbon atoms that are found in some of the constituents of paraffin and in the animal and vegetable oils and fats are not straight chains but zigzag ones, and it has been possible by means of *X*-rays to measure the lengths of such chains and their width, and as we can tell by chemical methods the number of the carbon atoms in the chain, we can calculate the angles made by the different parts of the chain. This method has led to a confirmation of the tetrahedral basis of the structure of many carbon compounds.

We have not quite finished with tartaric acid and the tartrates, but this little explanation about the tetrahedral basis of carbon compounds will perhaps make it easier to understand what we still have to say about the tartrates. We must consider tartaric acid as composed of two halves, each consisting of a  $\mathrm{H{-}\underset{|}{\overset{COOH}{C}}{-}OH}$, and this half can be represented by a tetrahedron with a carbon atom at the centre, a COOH group at one angle, an OH group at another angle, a H atom at a third angle; the fourth angle is connected with the other half of the tartaric acid molecule thus,



A. *B.*

These two structures are similar, but not identical; the one is right-handed and the other is left-handed. Moreover, the carbon atom at the centre of the tetrahedron is united to four groups, of which no two are alike, (*a*) an H, (*b*) an OH, (*c*) a COOH, (*d*) a group of  $\mathrm{H{-}\underset{COOH}{\overset{|}{C}}{-}OH}$.

We know, as the result of very many observations, that a carbon atom so placed—an asymmetric carbon atom, as it is called—will cause optical activity. The optical activity of the right-handed tartaric acid is due to the substance containing two halves of, say, the *A* type; the left-handed tartaric acid contains two halves of the other type; racemic acid consists of a compound of the right-handed and the left-handed tartaric acids; the optically inactive mesotartaric acid consists of one tetrahedron of the *A* type and one of the *B* type.

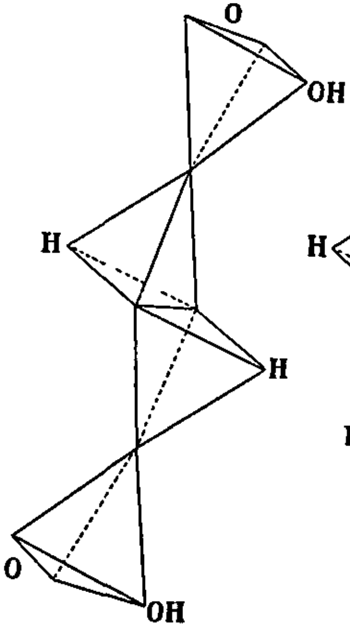
Tartaric acid in solution consists of a collection of such tetrahedral groups; a solution of the common variety of this acid rotates the polarized light in one direction, because each such group is arranged in the spiral fashion we have indicated. In the crystals of the common tartaric acid the groups of atoms are, for some reason that is not very easy to understand, differently arranged, and we have the astonishing result that the right-handed solution gives left-handed crystals. It has been suggested that the twist given to the polarized light by the large groups in the crystal is more than sufficient to neutralize the twist that it had previously received from the spiral arrangement of the atoms.

Pasteur knew that certain moulds, including a common one, Penicillium glaucum, flourished in a solution of the common right-handed tartaric acid and slowly destroyed it. He tried the effect of Penicillium glaucum on racemic acid, and found that the mould acted upon, and gradually destroyed, the right-handed part, but the left-handed part was not affected; this was one of the ways by which he was able to separate his new left-handed acid.

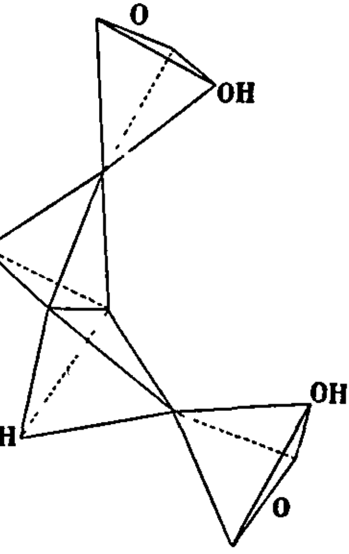
There are many optically active substances that occur in nature; the natural sugars, for instance, are optically active. In many cases chemists have been able to prepare in their laboratories both the right-handed and the left-handed varieties of the natural optically active substances; nature prepares only one. The moulds, yeasts, and similar organisms usually readily live upon, or convert into other substances, many of the natural optically active substances; as a general rule they do not act upon the corresponding substances of opposite activity prepared in the laboratory. Yeast acts very quickly on the ordinary sugars used in brewing; it usually is not interested in the sugars of opposite optical power made by the chemist. There is a lack of fit between the two; the nut easily fits on to the proper bolt; but a left-handed nut will not fit on to the same bolt as the right-handed nut.

Pasteur was led on from his experiments with the crystalline forms of the tartrates to investigate the nature of fermentation, then quite unknown. He was the first to realize that fermentation is caused by living organisms. This was a discovery of first-rate importance that we shall discuss later.

There are two distinct acids with the formula $HOOC \cdot CH{:}CH \cdot COOH$, fumaric acid and maleic acid, and if we represent the carbon atom by a tetrahedron, these two acids will be represented as follows:



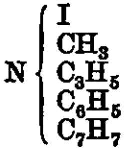
Fumaric acid.



Maleic acid.

We can see from this diagram of maleic acid that th more carbon tetrahedra would very nearly make a co plete ring, such as we find in benzene. Fumaric acid a maleic acid are not optically active; they differ from ea in both chemical and physical properties.

Carbon is not the only element that forms optical active compounds and so establishes the fact that compounds occupy space in three dimensions. In 18 Pope and Peachey made an optically active nitrogen co pound that may be represented by:



$$N\left\{\begin{array}{l} I \\ CH_3 \\ C_3H_5 \\ C_6H_5 \\ C_7H_7 \end{array}\right.$$

In the years 1899 and 1900, Pope, working in conjunctio with other chemists, prepared optically active compounds sulphur, selenium, and tin.

We have spoken of the asymmetric atom of carbon conferring optical activity on a compound, but there a optically active carbon compounds known that contain n asymmetric atom but have an asymmetric structure. Th fact that quartz is optically active shows that this variety silicon dioxide exists in three dimensions and cannot hav so simple a formula as O—Si—O.

CHAPTER VII

DIFFERENT VARIETIES OF THE SAME SUBSTANCE

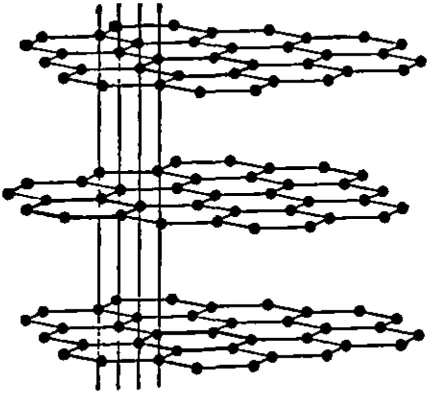
The diamond does not bear much resemblance to graphite or black-lead. The flashing diamond is associated in our minds with fashionable and wealthy ladies; it is a hard, colourless crystal, which can only be cut with great difficulty; it is found in the ground in a few localities and cannot be made artificially.

Graphite or black-lead is used to blacken our grates and fire-places; mixed with finely divided clay, it forms the writing part of the ordinary pencil. It is soft, crystalline, black in colour, and easily split into flakes; it is found in the native state in a few countries and can easily be prepared artificially.

Yet these two substances are both varieties of the element carbon; when they are burned they form the same gas—carbon dioxide—and the same weight of diamond or of graphite yields the same weight of carbon dioxide. It seems highly probable that these are the only two varieties of carbon, for charcoal, coal, soot, and lamp-black are not pure carbon. Coal is a mixture of carbon with obscure compounds of carbon and hydrogen, and of carbon, hydrogen, and oxygen. These compounds are black and not easily separated from black carbon. A similar explanation must be given of charcoal, soot, and lamp-black.

The differences between diamond and graphite all depend upon the way in which the atoms of carbon are connected together in the two substances. It has been possible by the use of X-rays to find out exactly how the carbon atoms are arranged and how far they are apart from each other.

In the diamond the atoms are fairly regularly spaced in all directions and the electrical attraction that binds the structure together is nearly uniformly distributed (see p. 130); in graphite the carbon atoms are arranged in layers separated by a greater distance from each other than the atoms in the diamond are: the effect of this is to produce planes of weakness, and so there is a tendency to form flakes. It is this tendency to form flakes that makes graphite a valuable lubricant; cast iron contains a small proportion of graphite, and cast iron is found to be a suitable metal for some of the moving parts of some internal-combustion engines. The reason for this is that tiny flakes of graphite are found on the surface of the cast iron and act as a lubricant.

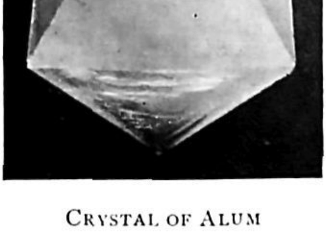


Arrangement of Atoms in Graphite.

We have all heard of oxygen and ozone; both are varieties of the same substance. The difference between these two is that the molecule of oxygen consists of two atoms of oxygen; the molecule of ozone consists of three atoms of oxygen. This is not quite comparable with the difference between diamond and graphite, for in crystals the atoms are

PLATE III

Medal Affected by Tin Plague

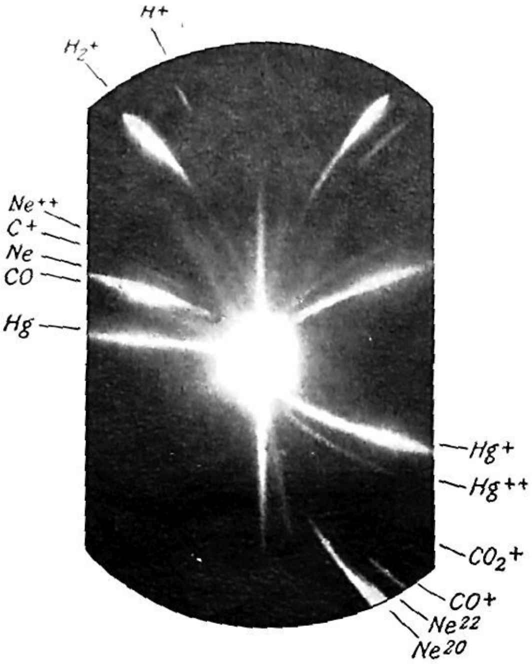


Crystal of Alum

[*E. Ray Lankester.*

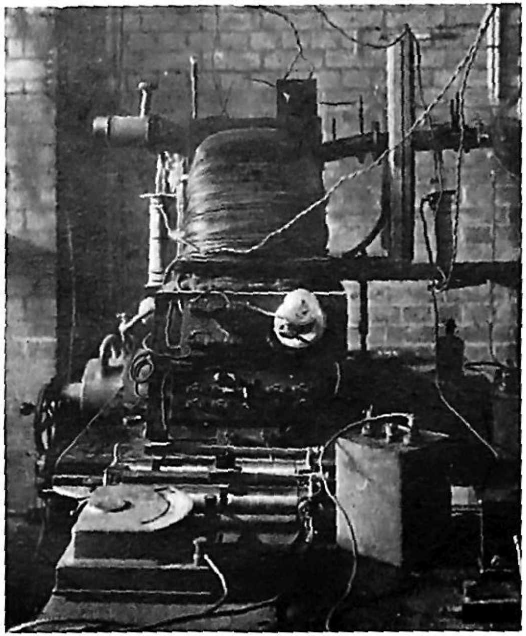
Imprint of a Fossil Jellyfish on Lithographic Limestone

PLATE IV



[F. W. Aston

THE PARABOLAS OF NEON (1913)



[F. W. Aston.

THE SECOND MASS SPECTROGRAPH

usually not grouped in molecules, but in larger aggregates. Ozone is popularly supposed to act as a tonic, but there is no evidence in favour of this. Ozone is rather an unstable variety of oxygen and it very easily oxidises other substances, and in this way it acts as a disinfectant of the air; the ozone is destroyed in the process of disinfection, and the presence of ozone in the air therefore often denotes that the air is fairly free from organic impurities. For this reason ozone is used in the London Tube railways as a disinfectant.

Sulphur exists in several different crystalline varieties, in one plastic variety, and in some other varieties. The element selenium, used in automatic devices for the detection of light, exists in two distinct varieties. Phosphorus exists in two main varieties: the yellow, which is very poisonous, and the red, which is much less poisonous. Tellurium, arsenic, silicon, zinc, and cadmium all exhibit this sort of property. It is quite probable that almost all the solid elements will be found to exist in more than one variety.

There are three or four varieties of iron that are known, and as iron is smelted, and cast, and annealed at temperatures that cover a fairly wide range, it has been found necessary to study the varieties of iron at many different temperatures.

Tin exists in more than one variety; that which exists at the temperature of the rooms we live in is a bright and shining, tough metal that retains a good polish. If such tin is kept for a long time in an unwarmed room during the winter, it becomes grey, dull, and powdery. Medals and vases kept in museums sometimes break out in spots and lose their shape and beauty through this so-called "tin disease" (Plate III). Solder, which is largely composed of tin, is also liable to this sort of decay in severe winters, and petrol has been lost because the tins have been left in the cold and the solder has perished. In the Scott and Amundsen

Antarctic expeditions the work was greatly handicapped by loss of petrol through this cause. Pewter which also contains tin is sometimes liable to this sort of trouble. Altogether three distinct varieties of tin are known. It is quite possible that this change is a cause of the trouble that sometimes occurs in the white-metal (tin alloy) linings of cylinders used in heavy motors equipped with Diesel engines.

There are also very many compounds that exist in more than one variety; for instance, calcium carbonate exists in two different crystalline forms, the one forming the well-known calcite or Iceland spar, the other with slightly different properties. Ammonium nitrate exists in three different varieties. The oxide of lead known as litharge exists in a red variety, a yellow variety, and a nearly white variety, and the last two easily change into the red variety.

Gases are composed of molecules made up of a few atoms, and we can therefore obtain only a few varieties of a gaseous element or a gaseous compound. Liquids consist usually of collections of more atoms, and solids of even larger aggregates. The more atoms you have to play with the more changes you can make in their arrangement, so we need not be surprised that there are seven different varieties of solid sulphur and three of ammonium nitrate. We shall find in a later chapter that there are also varieties of the atom of an element, an additional complication that is of interest.

It is sometimes possible to take a solid substance that is insoluble in water and grind it into such a fine powder that when it is mixed with water you cannot, even with the help of a microscope, see the individual particles. Such a mixture often looks like a solution, but it is really different. If a solution of common salt in water is placed in a parchment bag and hung in a jar of water, the salt will gradually penetrate through the parchment and enter the water in the jar. Parchment, like all other membranes, contains an enormous number of small holes, and there is a definite limit for the size of molecules which can pass through these holes. A mixture of water and finely-ground insoluble particles would behave differently from a solution of salt; the solid insoluble substance would be too bulky to penetrate through the minute pores of the parchment, but the dissolved particles of salt will easily pass through. The finely ground insoluble solid is in what is called the colloidal state, from a Greek word meaning glue.

Fine grinding is not the only way to make a colloidal substance. If a solution of gold chloride is mixed with tin chloride, a purple colour is obtained, called the purple of Cassius. The colour is due to the presence of colloidal gold. Colloidal gold is also used to give a ruby colour to glass and porcelain. It is possible by appropriate methods to prepare colloidal phosphorus, sulphur, selenium, platinum, silver, bismuth, iron, and many other metals. Some of the liquids containing colloidal metals are of great value in medicine. A colloidal variety of graphite is largely used as a lubricant. Silica is another substance that is easily obtained in a colloidal state, and the water-glass, used by many prudent housewives to preserve eggs, is a colloidal solution of a sodium silicate. Colloidal elements and colloidal inorganic salts are of interest and importance, but the colloidal substances in plants and animals are of far greater importance. True solutions can usually pass through a membrane, as a solution of common salt does, or a mixture of alcohol and water. On the other hand, colloidal bodies cannot pass through membranes, and as plants and animals are composed of an infinite multitude of cells, the walls of which are thin membranes, it is obvious that once a colloidal body is formed within a cell it will stay there until either the cell wall is torn or the colloidal substance is broken up. Most of the substances that go to make up plants and animals are colloids—for instance, starch, cellulose, and the various proteins.

When a solid body in a finely divided colloidal state is suspended in water, the solid particles are always electrically charged and so is the water but in an opposite electrical sense; for this reason, if a suitable electric current is applied to such a suspension, the solid may be collected together. Suspensions of colloidal substances have often curious properties. A preparation of a colloidal metal in water will usually be much more stable if some other substance of a suitable nature is added to it. Thus colloidal gold in water will remain stable for a very long period if a little gelatin or gum-arabic is added. Some of the colloidal suspensions made by Faraday have retained their properties almost unaltered for a period of more than sixty years. On the other hand, the colloidal gold will collect together and form a precipitate that falls to the bottom of the vessel if even a very small quantity of salt or an acid is added. Water dissolves a very minute quantity of glass, and even this is sufficient in time to destroy the ruby-red colour of colloidal gold in water.

It is not only possible to obtain small particles of solids floating in water for practically an indefinite period, but we can also obtain small drops of a liquid floating in a liquid that will not mix with the first. Such a mixture is called an emulsion, and milk is a very good example of this. Milk consists of small particles of fat floating in a solution of albumen, sugar, and a few other substances. These small particles are liquid at the temperature of an ordinary warm room, and if the milk is allowed to stand, some of them will rise to the surface and coalesce with each other. This operation takes place much more quickly if the milk is put into a centrifuge and whirled round at a suitable speed, the fat collecting as cream.

When milk is churned, instead of having drops of fat floating in a watery liquid, we get a more or less solid body that consists of drops of water suspended in a mass of fat that would be liquid but for the presence of the water.

Quite a small proportion of a solid substance may be sufficient, when mixed with a large proportion of liquid, to render the whole mixture a solid sort of jelly and quite a small proportion of a colloidal body, that is not a proper solid, may sometimes be mixed with a very large volume of liquid to make an emulsion that has every appearance of a solid. If about 5 per cent. of soap is intimately mixed with about 95 per cent. of methylated spirit, a jelly is obtained that burns when a match is applied to it. Other solid-looking jellies can be made by mixing a small proportion of olive oil very intimately with some watery solution. There are many different kinds of jellies, and some of them have very peculiar properties. Some of them very readily change from the solid state to the liquid state and back again. The change may be brought about even by shaking or stirring. There is a clay-like substance called bentonite formed from volcanic dust and found in the United States; if this is mixed with rubber latex (rubber juice), a plastic mass is formed which is liquid while being stirred but very quickly sets again to a solid. If such a mass is stirred and poured into a mould, it will fill all the cracks and crevices and the most intricate patterns of the mould, and will then solidify, so that when the mould is removed, the exact shape of the interior is preserved. At Solnhofen in Bavaria there is quarried a slaty-looking stone used for making lithographic plates; it contains about 95 per cent. of a very fine-grained calcium carbonate, and it probably originated as a fine dust deposited on a shallow beach. If this stone is finely powdered and mixed with ordinary water or sea-water, a plastic mass is made which is liquid while being stirred and solid at rest. There are various fossil remains in the Solnhofen stone, including the cast of so soft and watery an animal as a jelly-fish, and we believe that the only way in which this could be formed is that there happened to be, when the jelly-fish was in the proper place, a mixture of plastic mud that was capable of solidifying at once. This may afterwards have been covered by more mud, and ultimately the jelly-fish dried up, leaving its impression on the stone (see Plate III, p. 90).

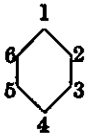
The fine suspensions of substances in water sometimes exhibit a singular phenomenon. The solid particles, if large enough to be seen under the microscope and if they are not too large, are seen to be in a constant state of movement, jerking about here and there, moving in a zigzag manner, sometimes rising and sometimes falling, but never at rest. This was first carefully observed in 1827 by the Scottish botanist Robert Brown, who was watching under the microscope a suspension of small pollen-grains in water, but it had been seen in earlier days by Buffon and by Spallanzani. The movement of such small particles is called the "Brownian movement," and we now know that the little jerks are caused by the water molecules or aggregates, which are constantly in motion, bumping against the pollen-grains, and knocking them now in one direction and then in another. A suspension of colloidal gold in water will show the Brownian movement under the microscope if a powerful beam of light is made to pass through the suspension and light up the gold particles which are otherwise invisible. Professor Zsigmondy of Gottingen described the movement thus: "A swarm of dancing gnats in a sunbeam will give one an idea of the motion of the gold particles. . . . They hop, dance, spring, dash together, and fly apart so rapidly that the eye can scarcely make out their movements." Professor Perrin of Paris made a very careful study of the Brownian movement and described it in his book, published in 1914, *Les Atomes*. From a study of a suspension of tiny fragments of the pigment gamboge suspended in water he was able to verify the statement made by Avogadro about a century earlier concerning the number of molecules in a given weight or volume of a substance. Avogadro showed that if the weight of a molecule of a substance is called *M*, then *M* grams of the substance will contain about 6×10^{23} molecules. Perrin, by observing the suspension of gamboge in water, obtained the figure $6{\cdot}06 \times 10^{23}$. By observing the Brownian movement of the suspended particles of tobacco smoke, de Broglie obtained the figure $6{\cdot}43 \times 10^{23}$.

So much for bodies in the colloidal state; there is a huge literature dealing with them, and we must devote a short space to some other instances of different varieties.

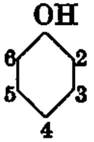
In addition to the rather inert nitrogen found in the atmosphere, it is possible to obtain nitrogen in a chemically active state. This is possibly a collection of molecules each consisting of three atoms of nitrogen. And there is an active variety of charcoal, called activated carbon, that has quite an exceptional power of absorbing various vapours. It is largely used for the recovery of vapours that escape into the air in various industrial processes, and also for recovering benzene from coal-gas. Charcoal obtained by heating coconut shells is particularly absorbent of many vapours, and during the Great War it was very largely used as a filler of gas masks.

We have been discussing in this chapter the varieties of exactly the same chemical substance; the substances we propose to mention next are not varieties of the same substance, but they are slightly different substances, yet having the same number of atoms and a very similar structure.

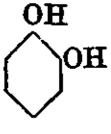
There are thousands of different compounds containing a benzene ring of six carbon atoms, each such atom being

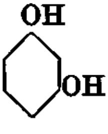


connected with a hydrogen atom. If we denote such a ring by a hexagon, and number each carbon atom, and ignore for the moment the hydrogen atoms, we obtain the diagram shown in the illustration. We can replace any one of the hydrogen atoms by a chlorine atom, an OH group, or many another group, and it is quite immaterial which atom we replace. Suppose we replace the hydrogen atom at 1 by an OH group, we shall then have this substance:



Now let us replace one of the other hydrogen atoms by an OH group, or a Cl atom, it does not matter which. We can effect this replacement in three ways: (1) by replacing an atom next door to the OH group, or (2) by replacing one next door but one, or (3) by replacing one opposite to the OH group. We shall thus obtain three substances that are slightly different from each other. These three will have a





general similarity in their properties, but will differ to some extent both in their chemical and physical properties. There will be also slightly different derivatives of naphthalene and of every other substance that contains a benzene ring. Fortunately we need not go into these in any detail. This is not a text-book of organic chemistry.

CHAPTER VIII

THE RARE GASES IN THE AIR

In the years 1892 and 1893 the late Lord Rayleigh was engaged in determining with great accuracy the density of nitrogen. This gas can be prepared in two ways: (1) from ammonium nitrite and other compounds of nitrogen, (2) by removing from the atmosphere—which is a mixture, and not a compound—the oxygen, water vapour, and carbon dioxide contained in it and leaving the nitrogen. Lord Rayleigh prepared nitrogen in both these ways several times, and measured the density of the nitrogen he obtained. Every time he found that the nitrogen prepared from the atmosphere had a higher density than that prepared from compounds of ammonia or compounds of nitrogen. He remembered that more than a hundred years previously Cavendish had taken a definite volume of air and passed an electric spark through it, which caused a combination of the oxygen and a part of the nitrogen. Cavendish absorbed by caustic potash the carbon dioxide that was originally in the air and the oxide of nitrogen made in the sparking process. Then he let in more oxygen and repeated the sparking; he continued to do this until he had combined all the nitrogen and there was a small surplus of oxygen. He absorbed this surplus, and found that there was a little gas left that he could not absorb, and his measurements showed that this gas could not have been more than $\frac{1}{120}$th part of the original air.

Rayleigh, who was a physicist, repeated this experiment, and at the end of 1893 he came to the conclusion that the only possible explanation was that the air contained some unknown gas that was heavier than nitrogen. Then he asked for the co-operation of chemists, and Sir William Ramsay helped him in 1894 to prepare a large quantity of the new gas. They called it argon, from a Greek word that denotes that it is chemically inactive; it has no combining power. The existence of the new gas and its strange property were received with some incredulity at first, but the evidence was so strong that there was no escape from the conclusions of Rayleigh and Ramsay. Argon is present in the atmosphere to the extent of about 1 per cent.; it is a colourless gas about two and a half times as heavy as oxygen or nitrogen.

In the following winter Ramsay was anxious to find some new sources of argon, and Sir Henry Miers advised him to examine a mineral, a kind of pitch-blende from which Dr. Hillebrand of the U.S. Geological Survey had in 1888 prepared a gas supposed to be nitrogen. Ramsay repeated the experiment, and obtained a gas which he tested spectroscopically, and he sent a portion of it to Sir William Crookes, the greatest expert in that subject in England. Crookes speedily replied to Ramsay, " Your new gas is helium."

At that time the element helium was not known, but its spectrum was, for in the solar eclipse of 1868 a new spectral line was observed by Frankland and Lockyer that could not be ascribed to any known element. It was supposed to originate from an element in the sun, and so the name helium was suggested for it. Helium is a colourless, inert gas, the lightest of gases with the exception of hydrogen; *one volume of oxygen is as heavy as eight volumes of* helium. It is present in the atmosphere to the extent of one part in 200,000.

It seemed, from the periodic table of elements, that if one inert gas existed there should be a whole family of inert gases, six of them, and Ramsay and his colleagues began a systematic search for the others. In 1898 Ramsay and Travers discovered three of the missing elements—krypton, xenon, and neon; the fourth—niton or radon—was discovered by Dorn in 1900. Krypton, xenon, and neon are contained in the atmosphere, but in small proportions, one part of neon in 65,000, one part of krypton in 1,000,000, and one part of xenon in 11,000,000 parts of air.

Although these gases were of great scientific interest, there was no demand for any commercial production of them until a further twenty years had elapsed. At that time it seemed that argon could become of industrial importance. The boiling point of argon is about 10° C. above the boiling point of nitrogen and about 3° C. below that of oxygen. When air is liquefied and the liquid air is distilled, the xenon distils over first, then the krypton, then the oxygen, next the argon, then the nitrogen, and finally a mixture of neon and helium. The various gases can be purified by redistillation and freed from nitrogen by metallic calcium or alkali metals. The neon and helium are finally purified by a systematic absorption by activated carbon kept at a low temperature by liquid air or liquid nitrogen.

Because it is chemically inert and has no effect on the filaments, argon is used for filling the bulbs of incandescent filament electric lamps, and tens of thousands of cubic feet are required every month for this purpose.

In America there are many places where a natural gas escapes from the strata, and this gas includes about 1 per cent. of helium. Helium is non-inflammable and is used for filling airships and balloons; millions of cubic feet of helium have been recovered from these natural gases.

Neon is used for display signs and advertisements, because when an electric current is sent through a tube containing neon a brilliant orange colour is produced.

It has quite recently been announced that in France krypton and xenon are being used instead of argon to fill electric bulbs. A higher rate of efficiency is claimed for such lamps, but it is necessary to liquefy 1200 tons of air in order to produce one pound of xenon.

Helium is not only found in the earth's atmosphere; it is also found in the sun and in some of the stars. The atmosphere of the earth differs in its nature from the atmosphere of the other planets, and these various atmospheres deserve a few minutes' consideration. The hotter a gas is the faster its molecules move; at the temperature of a frosty day—32° F. or 0° C.—the molecules of hydrogen move at the rate of 1·84 kilometres per second, the molecules of oxygen move at the rate of 0·46 kilometre per second, those of carbon dioxide at 0·39 kilometre per second. When, a few million years ago, the earth was much hotter than it is now, the gases in our atmosphere were travelling very much faster.

If we consider the earth's gravitation and its attraction for bodies moving in the atmosphere, such as molecules or cricket balls, we shall find that at moderate speeds the moving body will always return to the surface of the earth, but there is a critical speed, and above this a moving body *will take a curved path that will never return to the earth.* This critical speed is a high one—11·2 kilometres per second.

There is a different critical speed on the planet Mars—5 kilometres per second; that for the planet Mercury is 3·6 kilometres per second; for the moon the critical speed is 2·4 kilometres per second. When the earth was much hotter than it is now, probably a great deal of the then atmosphere flew away into space, and since then a new atmosphere has come into being. The oxygen in our atmosphere is supposed to be gradually accumulating from the oxygen given out by plants; the carbonic acid in our atmosphere may be partly due to carbonic acid emitted from volcanoes.

The moon and the planet Mercury have practically no atmosphere, and Venus and Mars have very little. The planets Jupiter, Saturn, Uranus, and Neptune have atmospheres very different from that of the earth. By means of the spectroscope it is possible to detect the presence of ammonia in the atmospheres of Jupiter and Saturn; if there was formerly ammonia in the atmospheres of Uranus and Neptune, it is believed that now it is frozen. The rest of the atmosphere in Jupiter and Saturn appears to be methane, a compound of one atom of carbon with four atoms of hydrogen, and this gas apparently forms the bulk of the atmosphere of Uranus and Neptune.

Our life on this earth, whether animal or vegetable, originated, in some way that we do not know, from the chemical elements in the water or air, or the soil, or possibly from all three. The higher plants and animals need not only a great variety of complicated chemicals; they cannot exist without air and water. The blood of animals is adapted to an air that contains oxygen; had our air consisted, like the air that surrounds Jupiter, of a mixture of ammonia and methane, we may be sure that such life as we are acquainted with would not have arisen; perhaps there would have been no life; we do not know; but there would have been no grass, no lilies, no fishes, no birds, no men and women. How life could possibly have originated here is a mystery that at this time we have no means of solving.

The substances that are built together to make herbs and trees, and rats and mice, and such small deer, are almost incredibly complicated. They are made up largely of carbon, oxygen, hydrogen, and nitrogen, and although we can now and then identify a group containing these four elements as present in many plants and many animals, we know very little about the origin or the nature of life. Life as we know it is an attribute of very complicated substances which contain at least these four elements, and we cannot conceive of life continuing in an atmosphere of methane and ammonia, for these compounds contain no oxygen. We do not know whether if we could prepare chemically a substance like the so-called protoplasm it would live and grow. Possibly our earth is the only planet or star on which life exists; it is improbable that the sort of life we are acquainted with is found on any of the other heavenly bodies that are known to us.

We have wandered a little from the rare gases; the mere mention of Jupiter and Saturn is enough to make us speculate. The rare gases are quite remarkable enough in themselves; their peculiarity is that they are chemically inert; they form no compounds or only a few that hardly count as true chemical compounds. Here is a list of the gases discovered by Ramsay and his colleagues with their atomic weights:

Element.	Atomic Weight.
Helium . . .	4·00
Neon . . .	20 20
Argon . . .	39 9
Krypton . . .	82·92
Xenon . . .	130·2

The last inert gas to be discovered—niton (also called radon), of atomic weight 222·4—is produced by the decomposition of radium and other radioactive substances, and is an unstable element like some others with high atomic weights. These rare gases have very different atomic weights and very different physical properties; we may say that they have no chemical properties. The electrical attraction of an atom of helium—in other words, its chemical affinity, its combining power—does not reach beyond the boundary of the atom. The helium atom has electrons in it, as all atoms have, but they satisfy the remainder of the atom electrically so perfectly that there is no vestige of attraction left over to enable the helium atom to attract any other atom. The helium atoms. the neon atoms, and the atoms of the other inert gases are absolutely self-centred, self-satisfied, solitary bodies.

This behaviour, or rather lack of it, does not depend upon the atomic weight; that is obvious. Atomic weight has not much to do with chemical activity. Chemical activity depends upon the number of the electrons attached to an atom and how they are distributed. We have learned something about these facts from a study of spectra, from *X*-ray investigations, from the behaviour of radium, and in other ways, and a very singular story they have to tell.

CHAPTER IX

HOW LIGHT AFFECTS MATTER

YEARS ago some experiments were carried out to try to prove whether thought could have any effect on matter; those people who believed that thought could have some effect remained of that opinion; the disbelievers also remained of their opinion, so everybody was satisfied. It has never been necessary to carry out experiments to prove that light may affect matter; that has been obvious for many centuries—ever since man placed a big stone on the ground and found out after a few days that the plants underneath were losing their green colour. We need feel no surprise about the effect of light on matter; matter consists of an almost infinite number of almost infinitely small particles; these particles are held together by electric attractions or electrons; light is a sort of travelling vibration, and it is powerful enough to disturb the electrons and introduce an element of unrest or even revolution.

In these modern days, when every house has its camera. it is needless to state that light is capable of altering such compounds as the silver salts on our printing-out paper. Colour photography is already known, and we now have television, and shall shortly expect to be able to see from our sitting-room our friends in their houses many miles away. With all these developments let us try to understand the mechanism of the action of light and how it helps us to obtain a knowledge of the structure of matter.

That light could affect the colour of some of the compounds of silver has been known for more than two hundred years, and Scheele paid considerable attention to this phenomenon as far back as 1777. We suspect that the Roman matrons were well aware that their fabrics dyed with the famous Tyrian purple faded in sunlight, but we do not recall any details of the complaints they made or, except from Theocritus, how they blamed their husbands for not buying goods of a better quality. The fading of purple fabrics was certainly known in the seventeenth century. Every careful housewife knows that white paint in the corner of a door or the inside of a cupboard is apt to turn yellow. They do not all know that this is caused by the darkening of the linseed oil with which the paint was mixed, and that the colour will be greatly improved if it is put into a strong light.

If hydrogen and chlorine in about equal volumes are mixed together in a glass jar in a dim light, nothing particular happens; but if the jar is taken into a bright light, the two gases combine together to form hydrochloric acid.

Wedgwood in 1802 seems to have made the first primitive photograph. Since that time every few years have seen some considerable progress in the art, the latest being the infra-red photographs that we sometimes see reproduced in our daily newspapers.

We have already shown that polarized light, in which all the vibrations are parallel to each other, has given us some knowledge of the spiral nature of molecules, crystals, and solutions; we have now to consider a subject that is rather more complicated.

Wollaston, the discoverer of the element palladium, was the first person to observe that when sunlight comes through a narrow slit and is refracted through a prism, the coloured band with red at one end and violet at the other is traversed by a number of dark lines. These lines were carefully studied by Fraunhofer a few years later, and are known as Fraunhofer's lines. He and subsequent observers found out that every chemical element, when put into a flame so as to become luminous, has the power of emitting light that is shown by the spectroscope to consist of a number of bright lines. Every dark line in the solar spectrum corresponds to a bright line in the spectrum of some known element. The Fraunhofer lines exist because the light has passed through the sun's atmosphere and the earth's atmosphere, and the different elements in these have absorbed the particular vibrations that are in harmony with their own structure. Just as the wireless apparatus can be adjusted to pick up a particular wave-length, so each element can pick up a number of light wave-lengths. If you sing the middle C in a room in which there is a piano and watch the wires, you will notice that the middle C wires are vibrating, but the D and E wires are not. The wire is affected by a note of the same nature as the wire itself is capable of emitting. The same sort of thing is true of chemical elements and light-waves. The waves of light, like sound-waves, have their own individual frequencies and wave-lengths. A chemical element, when it is heated, gives out light consisting of certain definite wave-lengths and under the proper conditions it will pick up vibrations of exactly those wave-lengths. When sunlight passes through the earth's atmosphere the oxygen absorbs rays of particular wave-lengths so that dark lines are found in the spectrum; if oxygen is heated it emits light with the same wave-lengths.

Very many of the elements that we are acquainted with on the earth can be recognized in the solar spectrum, and there are no lines in the solar spectrum that we do not attribute to some element that we know on the earth. There are no elements in the sun, or in any of the stars, except those known to us on this earth; this is a very remarkable and significant fact. All the matter in the whole solar or starry system is of the same type as the matter that we are acquainted with on the earth.

Of course, this sort of general statement is not perfectly true; very few general statements are. The more accurate statement is that there is no element known to exist in the universe that is not one of the 92 elements included in the Periodic Table of elements; 90 of these at least are now known to chemists and are found on this earth. The sun contains a great number of these elements; the meteoric stones that reach the earth contain some of these elements, in particular iron and nickel; some of the stars and nebulæ seem to consist of only the simple elements, of which hydrogen and helium are examples. It is a fortunate thing for the study of chemistry by mankind that all, or probably all, the elements are available on this earth. No one who had not actually worked on such elements as uranium, radium, and thorium would have dared to predict the very extraordinary properties these elements possess.

Seventy-five years ago there were several lines in the solar spectrum that could not be attributed to any element, but since then the elements to which the lines belong have been identified. And by studying minerals heated in a flame, several new lines have been detected that led to the discovery of new elements. It was in this way that the elements rubidium, cæsium, and thallium were discovered. The spectroscope enables us to say not only which elements are present in a particular flame, but also roughly in what proportions they are present. Some elements have spectra with a great many lines in them, some elements have spectra with only a few lines.

It is possible by suitable instruments to measure the wave-lengths of the lines in the spectrum of any element. Of all the elements, hydrogen has the smallest and the simplest atom, and its most usual spectrum has only a few lines. Many attempts, finally successful, have been made to find the relationship between the wave-lengths of the different lines, to discover some mathematical formula that could express them. If we denote by n the number of wave-lengths to the centimetre of any ray giving a line in the spectrum, we have to find an equation connecting the different values of n, and one such was found by a Swiss schoolmaster, Balmer, in 1885.

The wave-lengths of the light causing the lines in the hydrogen spectrum are very small; one of these lines is caused by vibrations of light with a wave-length of about 17,000 to one centimetre—that is to say, about 42,000 to the inch; another line is caused by light with a wave-length of about 20,000 to the centimetre; another line can be found, and the wave-length of the light causing it is about 22,900 to the centimetre. Balmer found that there was a definite relationship between these lines as follows: the wave-length of the first line was $\frac{5}{36}$ of 109,675 to the centimetre; in the second line the wave-length was $\frac{3}{16}$ of 109,675 to the centimetre; in the third line the wave-length was $\frac{21}{100}$ of 109,675 to the centimetre, in the fourth and fifth lines the numbers of wave-lengths to the centimetre were $\frac{8}{36}$th and $\frac{45}{192}$ of 109,675.

Now, these fractions may be expressed as follows :—

$\frac{5}{36}$ is $\frac{1}{4}-\frac{1}{9}$ or $\frac{1}{2^2}-\frac{1}{3^2}$
$\frac{3}{16}$ is $\frac{1}{4}-\frac{1}{16}$ or $\frac{1}{2^2}-\frac{1}{4^2}$
$\frac{21}{100}$ is $\frac{1}{4}-\frac{1}{25}$ or $\frac{1}{2^2}-\frac{1}{5^2}$
$\frac{8}{36}$ is $\frac{1}{4}-\frac{1}{36}$ or $\frac{1}{2^2}-\frac{1}{6^2}$
$\frac{45}{192}$ is $\frac{1}{4}-\frac{1}{49}$ or $\frac{1}{2^2}-\frac{1}{7^2}$

The series of all the possible lines of this sort can be represented by the formula $n = 109{,}675\left(\frac{1}{2^2} - \frac{1}{m^2}\right)$, where m is a small integer.

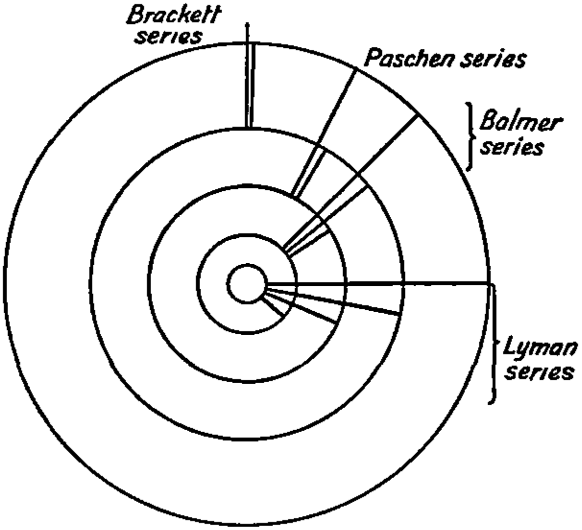
In 1906 Lyman found that some of the other lines of hydrogen belonged to a different series, $n = 109{,}675\left(\frac{1}{1^2} - \frac{1}{m^2}\right)$, where m is a small integer.

In 1908 Paschen found a third series in which other hydrogen lines could be placed, $n = 109{,}675\left(\frac{1}{3^2} - \frac{1}{m^2}\right)$, where also m is a small integer.

And in 1922 Brackett found a series for other hydrogen lines $n = 109{,}675\left(\frac{1}{4^2} - \frac{1}{m^2}\right)$.

These four series account for all the common hydrogen lines and most of the uncommon ones; similar series, with certain modifications, account for many of the lines in some other elements.

What is the meaning of these series? How do such lines come into existence? If the hydrogen atom is very strongly heated or electrified some of the electrons are driven much farther from the centre of the atom than their normal positions. They remain attracted by the rest of the atom, and so soon as they can find an opportunity, they return to their usual abodes. When they do this, they cause the disturbance registered by the bright lines in the spectrum. The electrons are not driven away to indefinite distances, but to certain definite ones denoted by the circles in the diagram shown on page 112. The Brackett series is caused by a return of electrons to the fourth imaginary sphere outside the hydrogen atom. The Paschen series is caused by a return of electrons to the third of these imaginary spheres; the Balmer series by a return to the second imaginary sphere; and the Lyman series to the first imaginary sphere. We have spoken of these external positions as if they were on imaginary spheres; imaginary ellipsoids would probably be nearer the truth, but it is not so easy to show these on a diagram, and this diagram is only a rough approximation; it is impossible to make an accurate drawing to scale of the possible travels of the electrons.



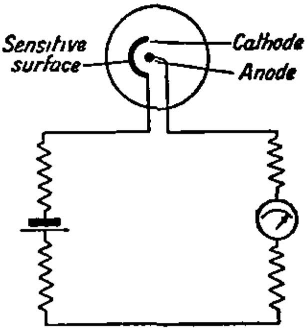
The photo-electric cells that are now used as controls in factories and in television are of great interest. They are of two kinds. In the first kind the element selenium is employed. Selenium resembles sulphur in its chemical properties, but not in its physical properties. It exists in several varieties, one of which is a greyish, metallic-looking solid, which has the very unusual property that its electric conductivity is greater in light than in darkness. If we construct a valve containing selenium and place this valve in an electric circuit, an increase or a decrease in the light falling on the valve will alter the current flowing in the circuit, and it is easy to arrange for such an alteration to ring a bell, or to light a red lamp, or in some other way to call attention to the fact that something abnormal has happened.

The other kind of photo-electric cell depends on a different principle. All substances contain an immense number of minute particles of electricity—electrons—and it is possible in many ways to remove the electrons that lie on the surface of the substance. If we rub a stick of ebonite or sulphur with a suitable cloth, or brush our hair in frosty weather, we rub off some of the electrons, and we can thus obtain an electric spark. If we heat a metal to a high temperature, we shall dislodge a number of the electrons, and can obtain an electric current if the apparatus is suitably designed. Some elements give up the electrons on their surface when exposed to light, and three elements—potassium, rubidium, and cæsium—have this property to a remarkable extent. If the diagram of atomic volumes on pages 56 and 57 is referred to, it will be noticed that the elements cæsium, rubidium, and potassium have exceptionally large atomic volumes. In other words, one at least of the electrons is exceptionally distant from the centre of the atom of these elements. Whether this is the reason for these elements giving off electrons on exposure to light is not certain. In television a valve is used containing an anode and a cathode enclosed in a bulb with a small quantity of one of the inert gases, the anode and cathode being connected up with an electric circuit and a galvanometer.

The cathode consists of a rounded saucer of metal, one surface of which is covered with potassium or cæsium. On exposure to light a current will flow, the strength of which depends on the strength of the light.

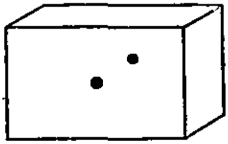
By passing an electric current through mercury vapour or neon, a light is obtained, and such a lamp is very sensitive, and is the best to use for the re-conversion of the electricity back to light.

It is easy to see how a spot of light in one place, or two or three spots of different intensity, can be reproduced at a place many miles away, using wireless waves as part of the electric circuit; but the reproduction of a picture is not so easy. It is effected by a process known as scanning—that is, reproducing the picture in narrow strips, each strip being exposed and reproduced for a very brief space of time, about a twelfth of a second. The eye is very quick in receiving an impression, but the vision persists for a short time after the cause of it has ceased: a light rapidly moving in a circle may appear as a stationary circle of light; a set of narrow strips adjoining each other, each being exhibited for a twelfth of a second, looks like a picture.



There are two other very interesting principles that can be made use of in television, and they illustrate the way in which matter is constructed and may be altered, and this is supposed to be one of the subjects of this book.

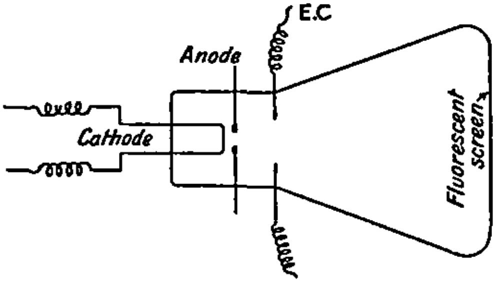
A very common crystal is calcite (Iceland spar), a crystalline form of calcium carbonate, $CaCO_3$. If a crystal of calcite is placed on a piece of paper with a spot on it, you can see two spots, if you look through the crystal. The reason for this is that a beam of light entering the



crystal in a particular direction is split up into two beams by the atoms it meets. One beam continues to travel through the crystal in the same direction in which it started, the other is deflected in a different direction. The first beam is called the " ordinary " ray, the latter the " extraordinary " ray. Now, both rays, on their passage through the crystal, are polarized—that is, in a ray or set of rays only vibrations in one special direction are found. The direction of polarization of the ordinary ray is parallel to the plane of the CO_3 group in the crystal. A beam of light that has been polarized by its passage through a crystal of Iceland spar will easily travel through another crystal the sides of which are placed parallel to the direction of the sides of the first crystal, but if the second crystal is rotated or put at a different angle, much of the beam of light will be deflected by the second crystal, and only a small part of it will eventually emerge in the same direction as it started. It is possible mechanically to rotate the second crystal, and so increase or diminish the light travelling through two crystals of Iceland spar, but it is also possible by an electric current to rotate a beam of polarized light, and so, if you take two crystals of Iceland spar, one behind the other and with the sides parallel, and set up an electric circuit between the two crystals, you have an apparatus that will allow a small or large amount of light to travel through the apparatus in accordance with the strength of the electric current.

You can thus have an apparatus at one end of a wire, such that the strength of the electric current flowing through the wire depends on the strength of the light reaching the apparatus, and you can have at the other end of the wire a valve which will regulate the emission of light in accordance with the strength of the current. This is the principle upon which television depends.

Another piece of apparatus that is used in television is the cathode-ray tube. When a metal is heated, electrons escape from it, and after this was found out, it was easy to make an apparatus of this nature :



The wire that forms the cathode is electrically heated, and gives off a stream of electrons that passes through the hole in the anode and finally hits the fluorescent screen in the bulb; the bulb contains just a trace of an inert gas. Where the cathode stream hits the fluorescent screen there will appear a spot of light. By means of the electric circuit marked E.C. in the illustration, the stream may be deflected either horizontally or vertically, and such a piece of apparatus is obviously suitable for television.

Whatever method is adopted, a current of electricity that varies with the intensity of light in the strips of the picture is transmitted to the receiving end, and then illuminates a neon or mercury vapour lamp, the strength of the illumination depending upon the varying strength of the electric current.

It is sometimes possible to be more precise in stating the action of light on a chemical substance.

Ordinary light is a mixture of lights of many different colours, each colour having a different wave-length; the yellow light of a flame coloured by sodium has a wave-length of 5895 Ångström units, the Ångstrom unit being one hundred-millionth of a centimetre, usually written A. The green thallium flame has a wave-length of 5351 A.; blue and violet lights are of shorter wave-lengths. Besides the varieties of light which are visible to the human eye, there are varieties of vibrations of a similar nature to light that lie outside the limits of the coloured spectrum, a series of infra-red rays with wave-lengths up to 4,200,000 A., and a series of ultra-violet rays with wave-lengths down to about 150 A. It is not only the light of the visible spectrum which is chemically active: the ultra-violet rays and the shorter infra-red rays are also chemically active. The various rays are by no means of uniform chemical activity; if we consider the activity of the light of a particular wave-length from its usefulness in photography, we find that for one sort of plate a red light is particularly good, for another sort of plate a blue light is particularly good. For plates treated with special sensitizers ultra-violet light is needed, and it is possible to make sensitizers suited for several different parts of the visible and the invisible spectrum. A particular wave-length is often stimulating to a special chemical reaction.

As we have seen, when a body is heated so as to be red hot, the electrons are driven farther away from the centre of the atom, and they find their way into various different levels; the passage of a number of electrons from one level to another level nearer to the centre gives out the phenomenon which we call light, and for each element there is a line in its spectrum that corresponds to a change of electrons from one level to another. We speak of levels rather than spheres, because spheres gives us a definite picture that is easy to understand, but we are not really justified in assuming that the electrons are driven away to positions all at an equal distance from the centre of the atom; the change of position of the electron is often spoken of as a change of its energy level, and this is in some respects a more accurate way of describing it, even if we do not say what we mean by energy level. Each element has its own spectrum, and this implies that each element has its own arrangement of electrons at its own energy levels, and the transference of its electrons to new positions is connected with the phenomena of light. We find that some elements and many compounds can be stimulated by light to a condition of greater activity, and the sort of light that is specially stimulating is usually the sort of light that the substance emits in its spectrum.

The action of light on chemical compounds is particularly noticeable in green plants. A particular colouring matter in a plant, for instance, may have a set of lines in the yellow or the red part of the spectrum. Light with this wave-length may be exciting to the molecules of the colouring matter. The green colouring matter of plants—chlorophyll—not only produces a beautiful colour; it enables the plant to absorb carbon dioxide from the air and to combine it with the plant's watery juices to make sugar, starch, and other compounds. The chlorophyll requires the stimulus of light, and lights of one or two particular wave-lengths are the most effective. In the human body ultra-violet rays may stimulate a chemical action—for instance, the formation of a vitamin, when ordinary visible light has very little effect. Electrons are like human beings in one respect: they may need a stimulus to stir them to a due state of activity. One such stimulus is a vibration with a wave-length that exactly suits their individuality. One electron may be exactly like another when considered as a separate entity, but the set of electrons in silver does not behave like the set of electrons in oxygen or sulphur, and will probably need a different stimulant.

CHAPTER X

X-RAYS

THE dependence of discovery on improvements in apparatus, which we have mentioned, may be illustrated by the discoveries made possible by Sprengel's mercury pump for producing a more nearly perfect vacuum than had previously been possible. This pump was invented in 1865, and in the next ten years several men experimented on the radiation that can be produced by passing electricity through a "vacuum tube" containing a very minute quantity of some chemical element. Among these workers the most renowned was Sir William Crookes, who invented the well-known radiometer the vanes of which are made to revolve by the impact of molecules of the vapour in the nearly evacuated tube. When an electric current is passed through a vacuum tube containing a very small quantity of a gas, the tube is filled with a glow or light, except a dark space near the cathode or negative terminal; this is called "Crookes's dark space," and Crookes paid a great deal of attention to studying it and the rays that come from the cathode. His paper on this radiation in 1879 attracted much attention.

In 1895 Professor Rontgen of Wurtzburg discovered that when such cathode rays are allowed to strike a solid body, they can set up a new sort of radiation, which has the remarkable characteristic of passing through flesh, paper, wood, thin sheets of aluminium, and other substances. The rays so produced were formerly known as Rontgen rays, but are now universally known as *X*-rays. They have the power of acting on photographic plates, and it is superfluous to remark on the value of *X*-ray photographs in medicine and surgery. While the study of *X*-rays was being pursued by others, the cathode rays were in 1891 studied by Sir J. J. Thomson, for many years head of the Cavendish Laboratory at Cambridge and now Master of Trinity.

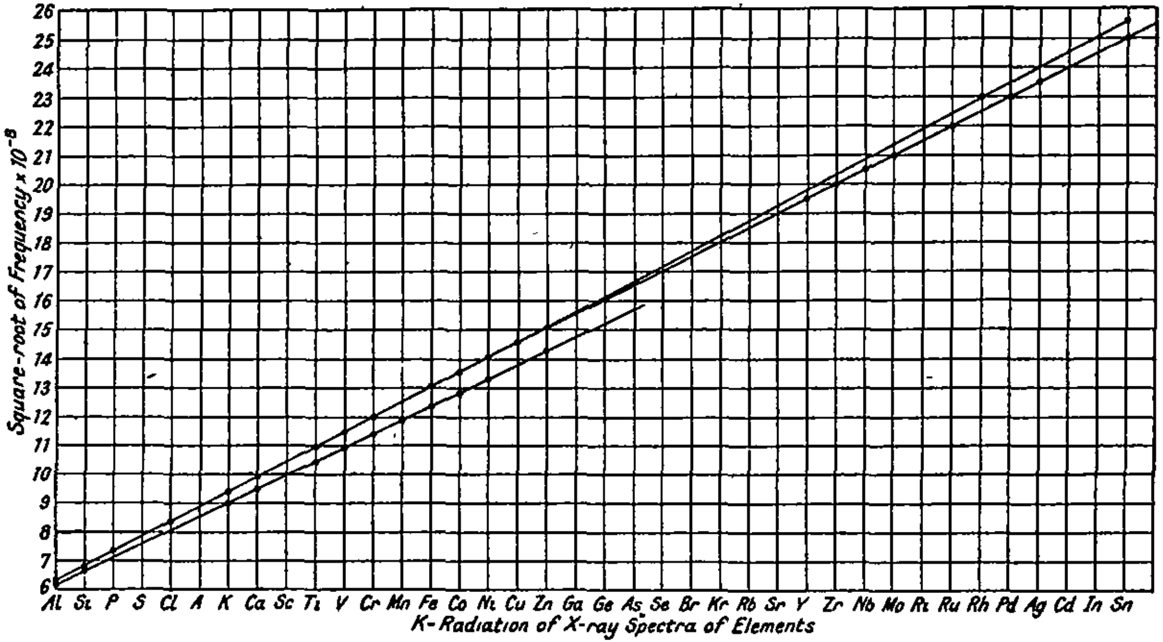
He investigated the velocity of the cathode rays and their electrical charge, and he found that the rays behaved in some respects as if they were composed of tiny particles of matter; finally, he was able to satisfy himself and others that the rays were really streams of rapidly moving little units of electricity. It had been suspected that such units existed, and they had been named " electrons " by Johnstone-Stoney, but J. J. Thomson was the first to study them, calculate their speed, and the amount of matter they contain. They do not contain very much matter; the hydrogen atom was supposed to be the lightest particle known, but the electron only weighs as much as $\frac{1}{1840}$th of a hydrogen atom.

Sir William Crookes wrote about this in 1902: " In twenty-five years one's theories may change, although the facts on which they are based remain immovable. What I then called ' Radiant Matter ' now passes as ' Electrons,' a term coined by Dr. Johnstone-Stoney to represent the separate units of electricity which is as atomic as matter. What was puzzling and unexplained on the ' Radiant Matter ' theory is now precise and luminous on the ' Electron theory.' "

In an *X*-ray tube there is a high vacuum in which there is a cathode at one end, from which a stream of electrons is transmitted through the tube towards a disc facing opposite the stream; this disc is called the anti-cathode, and on it there is placed the body to be investigated. In modern types of this apparatus the electric current is often from

30,000 to 70,000 volts, and a part of this energy is converted into *X*-rays, while the remainder is converted into heat. In 1908 Barkla, who was then working in the Cavendish Laboratory, discovered that the different elements gave out a radiation when they were exposed to cathode rays or to *X*-rays; this radiation is characteristic of the particular element used, and most elements emit a radiation that may be compared to a spectrum, in that it consists of lines each of which has a definite wave-length. Many of the elements give *X*-rays spectra consisting of two sets of lines called the *K*-series and the *L*-series (Plate V, p. 166). The rays in these two series may be diffracted by a crystal, and so it is possible to measure their wave-lengths.

Moseley at the Cavendish Laboratory in the years 1912 and 1913 measured the *X*-ray spectra of a number of elements, using in this work the diffraction caused by an excellent crystal of potassium ferrocyanide that is still preserved there. He found that the *X*-ray spectra varied in a very regular way from one element to the next element in the periodic table. A vibration, such as light or an *X*-ray, resembles a moving set of waves; there are so many waves to the centimetre, and so many waves to the second. The number of waves to the second is called the frequency, and in the case of light and *X*-rays it is a very large number. When the square root of the frequency of the lines in the spectrum is plotted on a chart against the position of the elements in their order in the periodic table, nearly straight lines are obtained. Moseley's law enabled chemists to do what had never been previously possible: to arrange the elements precisely in their proper order, and to say how many still remained to be discovered. By proper order is meant the order that is most in accordance with the chemical and physical characteristics of the elements. Moseley's diagram of the *K* spectra of the elements from aluminium to tin is shown in this diagram:


Square-root of Frequency × 10^{-8}
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Al Si P S Cl A K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo Ri Ru Rh Pd Ag Cd In Sn
K-Radiation of X-ray Spectra of Elements

The elements with very small atomic weights, the first ten in the periodic table, are not suitable for *X*-ray examination; all the others can give the *K*-radiation. The elements from sodium to nickel (Nos. 11 to 28 in the periodic table) give no other radiation, but from copper (No. 29) onwards the elements give the *L*-radiation also. In the year 1916, Siegbahn discovered that there is also an *M*-radiation that can be measured for a number of the rare-earth elements and the other elements later in the periodic table; moreover in 1922 a fourth series—the *N*-radiation—was discovered by Hjalmar; it is only observed in the elements bismuth, thorium, and uranium, which have high atomic weights and come towards the end of the periodic table.

As we travel up the periodic table the atoms become heavier and more complicated; the very simplest of all are incapable of yielding a radiation; then they yield one series, after a time two series, later in the table three series, and finally four. These five stages obviously represent five stages of complication in the atoms. It is reasonable to assume that we are dealing with four or five imaginary spheres or ellipsoids such as were mentioned in the last chapter. This is no proof, merely an assumption; it may be worth examining, all the same. It is convenient to give these spheres or ellipsoids a name, and they are now commonly spoken of as "energy levels," a vague term, because our knowledge of this matter is itself a little vague. All that the term "energy level" means is that a certain amount of energy is needed to drive electrons away from the centre of an atom, whether they are moved away in spheres or not, and that an increase in the energy may drive the electrons to new positions still farther away. They will go by jumps from one set of positions to another, like an army advancing from one set of trenches to another during a battle; the electrons, like the soldiers, do not dally between the trenches; they hurry from one position to another, stopping only in the appointed places.

Is there any connexion between the energy levels concerned in light spectra and the energy levels concerned in *X*-ray spectra? We are afraid there is not. The lines in the visible spectrum have wave-lengths of about 5000 Ångström units; most of the lines in the *X*-ray spectrum have wave-lengths less than 5 Ångström units. The visible spectra are typical of gases and vapours; the *X*-ray spectra are typical of solids. The visible spectra are emitted as the result of stimulation by heat; the *X*-ray spectra are stimulated by electricity. The *X*-rays are tiny little things when compared with the rays of light, and the movements of electrons concerned in *X*-ray spectra are very much less than the movements of electrons concerned in visible spectra. Hydrogen has no *X*-ray spectrum; it has a complicated visible spectrum. The only point of resemblance between the visible spectra and the *X*-ray spectra is that both are produced by vibrations or waves.

Since the invention of the wireless we are all familiar with wave-lengths, and the enthusiasts can tell you offhand the wave-lengths used by London Regional, Rome, Prague, and other places. The wireless waves or vibrations are propagated through space with an incredible velocity, and they form a part of a huge system of such vibrations or rays that can be prepared by various means.

Let us consider this system for a few moments. The waves with the longest wave-lengths have a wave-length of about 20,000 metres—roughly about 12 miles; they are too awkward to be of much use for our present wireless apparatus; but those with a wave-length of about a tenth of this—say 2000 metres—down to a wave-length of about 16 metres, are commonly used in wireless work. There are also shorter vibrations with wave-lengths from about 16 metres to about 400 microns that are not used at the present time—a micron is a millionth of a metre, and a metre is about forty inches, so that a micron is much less than the thickness of a sheet of paper. As we come to still shorter waves we find those whose wave-lengths are small enough to disturb the atoms in certain chemical substances. We all know the visible spectrum; we see a part of it in the rainbow and the same part of it when light is passed through a prism. But the human eye is adapted to see only a small part of the spectrum that can be detected and measured by photographic plates. Outside the red end of

WAVE-LENGTHS OF VARIOUS VIBRATIONS.

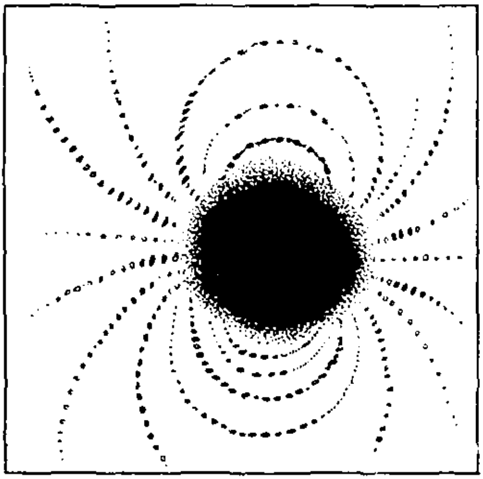
	Ångström units.	Microns.	Metres.
Cosmic rays	0·0005–0·01		
γ-Rays	0·01–10		
X-Rays	10–150		
Ultra-violet rays	150–4000		
Visible spectrum	4000–7000	0·4	
Violet	4000–4240	0·4 –0·42	
Blue	4240–4912	0·42–0·49	
Green	4912–5750	0·49–0·57	
Yellow	5750–5850	0·57–0·58	
Orange	5850–6470	0·58–0·64	
Red	6470–7000	0·64–0·7	
Infra-red	7000–4,200,000	0·7 –420	
Hertzian waves		420–20,000,000,000	0·0042–20,000
Schenectady			19·5
Pittsburgh			19·7
Madrid			30
Aberdeen			233
Poste-Parisien			312
London Regional			342
Vienna			506
Droitwich			1500
Hilversum			1875

the visible spectrum are the infra-red rays that photographers use for long-distance work, rays that will easily penetrate through a mist. Infra-red rays have been measured with wave-lengths from 420 microns down to 0·75 of a micron. Next we come to the visible spectrum, the extreme red end of which is about 0·75 of a micron and the extreme violet end of which has a wave-length of about 0·4 of a micron. There is a great length of spectrum outside the violet end of the visible spectrum—the ultra-violet rays, that affect photographic plates, sunburn our backs at the sea-side, and help to cure certain diseases. The ultra-violet rays have wave-lengths from about 0·4 micron down to about 0·01 micron. They merge into the *X*-rays, waves whose lengths range from 0·01 micron down to about 0·00001 micron. Still shorter rays are the γ-rays and the cosmic rays, of such short wave-lengths that the mind of man can only gasp at the array of noughts in the decimal fractions of the micron that denotes them.

If you have a set of waves following each other at regular intervals, there may come a time when the waves reach a surface that will reflect the waves, not exactly in a direction opposite to the course they have already taken, but at some angle to this. The result of such a reflection will depend on a variety of circumstances, but the reflected wave will sometimes meet the incoming wave, so that the crest of each is in the same place at the same time; this will make the wave larger. Somewhere else two waves will meet so that the crest of one fits in with the trough of the other and they cancel the effect of each other. The general result will be that, instead of a regular succession of small waves, you will get a set of fewer waves but bigger ones and also a set of no waves. If we take a score of glass plates each, say, a hundredth of an inch thick and pile them one on another, it would be possible to put a light in such a position that it would be reflected from twenty different surfaces, all in the same direction. You would get no great waves of light by such a reflection, because the light waves are so very tiny by comparison with a hundredth of an inch. But if we could get a set of reflecting surfaces all parallel to each other and separated by a distance of, say, four or five times the wave-length of light, we should find that, instead of a uniform light, we should get bright lines or spots and dark lines and spots. Perhaps a powerful microscope would be necessary to see the bright lines or spots. A crystal usually consists of parallel layers of atoms or groups of atoms and it is possible to reflect waves from these layers so as to get a regular succession of lines or spots. Such a regular succession is called an "interference pattern," and the measurement of interference patterns has been carefully studied in connexion with waves of light, *X*-rays, and other waves.

It is not necessary to have a set of reflections in order to obtain interference patterns; these can be obtained if the vibrations or waves are bent out of their course by a change of circumstances—for example, when light travels through air and afterwards through water or glass. A ray of light meeting a surface of water or glass at an angle is bent or diffracted to a different angle, and if such diffraction is caused by a set of layers not very much greater than the wave-length of light, then there will be interference patterns.

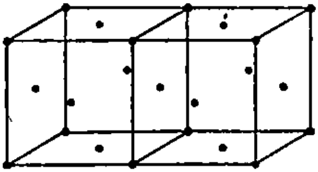
Gratings of flat surfaces ruled with thousands of parallel lines to the inch have been manufactured and used for many years. The beautiful colours displayed by a butterfly's wing or a peacock's feather are often caused not by pigments, but by a multitude of fine ridges or lines. So are the brilliant colours on the wing-cases of some beetles. Thin films of liquids, such as are obtained if a drop of oil is dropped on a sheet of water, can also cause colour effects comparable with those which arise from a set of parallel lines ruled on a sheet of glass or silver; the colour effects are best when the thickness of the oil film or the distance between the parallel lines is about the same, or only two or three or four times as much, as the wave-length of light.



Laue Pattern from Nickel Sulphate.

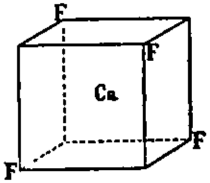
In 1912 it occurred to Professor Laue that a crystal containing a set of parallel rows of atoms might act as a grating and give diffraction patterns. Accordingly, an experiment was made by Friedrich and Knipping in the laboratory at Munich. A beam of *X*-rays was passed through a crystal and allowed to fall on a photographic plate. The plate, when developed, showed a number of spots arranged in a definite pattern, and when a crystal of zinc blende was used, it was possible to show that the pattern agreed with the structure of the zinc blende that had been supposed by chemists to fit the form of that crystal. Sir William Bragg and his son, Professor W. L. Bragg, were able to calculate a law for the interpretation of such diagrams, and they have been able to determine with a high degree of probability the way in which the different atoms are arranged in hundreds of crystals.

Zinc blende is a sulphide of zinc, ZnS, and it has been shown that in zinc sulphide the zinc atoms lie at the corners of cubes and the centre of the cube faces thus :

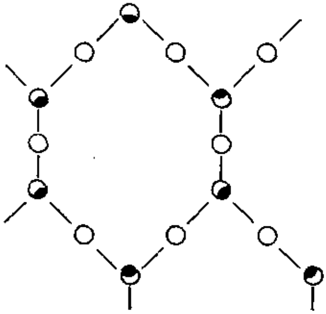


The black spots indicate the zinc atoms, but the atoms in the centre of the cube faces at the back have not been shown. The sulphur atoms also lie at the corners and face centres of cubes, but a different set of cubes.

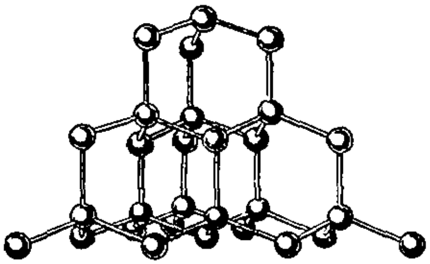
In fluorspar, or Blue John, calcium fluoride, CaF_2, the atoms of fluorine are placed at the opposite corners of the sides of a cube and the calcium atom in the centre of the cube thus :



In the great group of the mixed silicates of aluminium, calcium, potassium, and other metals, which form the felspars, micas, and so many other common minerals, the positions of the SiO_2 (silica) groups have been determined by investigations extending over many years. It is unnecessary here to give all the details, but in some of these minerals the silicon and oxygen groups are arranged as follows, the black circles denoting silicon and the white circles oxygen:



In the diamond the carbon atoms are arranged in this manner:



The first attempt to use *X*-rays to analyse organic compounds was made in 1921 by Professor Sir William Bragg, who measured the smallest units of naphthalene and anthracene; he was able to determine the absolute size of these units and the angles included by their sides and the probable position of the carbon rings in the unit cell. The hydrogen atom is so much smaller than the carbon atom that the *X*-ray analysis of naphthalene and anthracene did not disclose the positions of the hydrogen atoms.

Very many other examples could be given, and they will be found in the text-books dealing with *X*-rays. It is not necessary for us to do more in this chapter than to show the way in which X-rays have helped us to learn how the various atoms are placed in crystals. Large crystals were used by the early workers in X-ray analysis, but in 1916 it was found that an extremely fine powder consisting of tiny crystals and fragments of crystals could also be used for this purpose

CHAPTER XI

ELEMENTS THAT EMIT RAYS

During the last five years of the nineteenth century and the first thirteen or so years of this century our ideas of the chemical elements underwent a revolution. We had to abandon some notions that had been accepted as fundamental principles for a century and to accept some new ideas of rather a startling nature. Fresh discoveries that seemed almost incredible were made almost every year but they were made by careful observers, and could not be ignored, and we were compelled to adjust our conceptions of elements and atoms so as to fit in with the stream of new facts. The new conceptions were fairly startling to old-fashioned students who had been taught to believe that every element was of one specific kind, constant and everlasting, and that every element could combine to form chemical compounds. They thought that any attempt to penetrate inside the atom was doomed to disappointment: it was so tiny, and those of us who then studied chemistry had been accustomed to think that it was a sort of unit, incapable of division, destruction, or alteration.

We now know that many elements are continually undergoing a change into some other element; that these elements are neither constant nor everlasting. We know that practically all the elements are composed of two kinds of matter, or two parts, one chemically active and the other chemically inactive, and we find that one particular element does not always contain the same proportion of the active and inactive kinds. We know a great deal of the way the various atoms are built from smaller constituents, making use of one or two kinds of bricks and only one kind of mortar, and producing ninety or so different elements. And we have made the acquaintance of elements that are not known to take part in forming chemical compounds. Perhaps the strangest of all these ideas is the automatic transmutation of one element to another. We will now explain how this takes place.

In 1895 Professor Becquerel of Paris was working at the phosphorescence of some compounds of uranium, and he found that these compounds had a singular property. They were continually giving off rays of some sort that were not visible to the eye, but were capable of acting on a photographic plate. These rays—or this radiation, as we may call it—had the power of making a gas, usually a non-conductor, into a conductor of electricity. Professor Curie of Paris and his wife, Mme. Curie, studied the radiation of uranium compounds very carefully, and in the year 1898 announced that they had discovered two new elements that they found to be always associated with uranium; these elements they called radium and polonium. Uranium, radium, and polonium are not very plentiful elements; they occur in a mineral called pitch-blende, that is not found in large quantities, and the proportion of radium in pitch-blende is very small—about one part in a million. Pitch-blende is an old name for the mineral, but a misleading one, for it has nothing to do with pitch or with blende. In this it is as unfortunate a word as is cockroach. Radium is a metal somewhat resembling calcium and barium in its chemical properties. Its other properties are quite remarkable; it is continually giving off a radiation consisting of three distinct kinds of rays, and a gas or emanation. The three rays are known as α-rays, β-rays, and γ-rays; the emanation has been called niton or radon. Radium is continually undergoing the change we have mentioned; it does not give off a fixed quantity of radiation every week and lose a fixed amount of its substance, but it loses a fixed proportion; a quantity of radium weighing, say, two grammes would in about two thousand years have diminished to about one gramme. In the course of another two thousand years it would have become half a gramme, and so it goes on, losing about half its weight in a couple of thousand years.

The emanation is much more unstable than radium; it is a gas that chemically resembles argon and neon. It is chemically inactive, but it has an intense physical activity, giving off α-rays and losing half its weight every four days, and leaving behind another radioactive element that is chemically identical with polonium and belongs to the same group as the elements sulphur, selenium, and tellurium. This radioactive element has been named Radium *A*. It is an unstable element that gives off rays and undergoes a series of transmutations, chopping and changing its mode of life and squandering its substance gradually, as radium does, until finally it ends up as that respectable element lead, as unchanging as anything in this world. This gradual change, through all these steps, of radium into lead is an extraordinary thing to happen, but it is not the whole story.

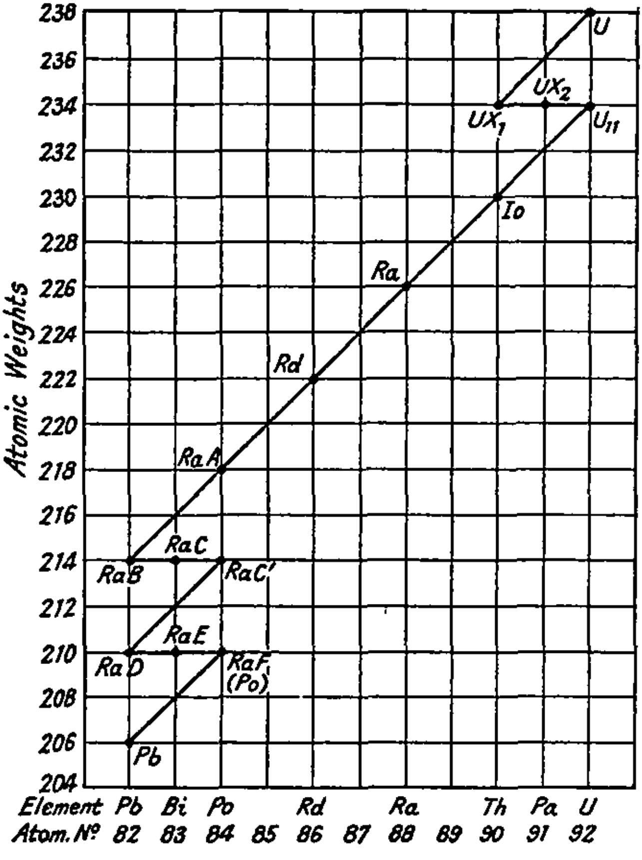
In 1898 Mme. Curie, and Schmidt quite independently, discovered that the element thorium is also radioactive—that is, it gives off rays and is gradually converted into some other element. In 1899 another radioactive element, actinium, was discovered by Debierne. Thorium and actinium go through a set of changes, ultimately forming lead, as radium does. Other radioactive elements have since been found.

Professor Rutherford, now Lord Rutherford, investigated the radiation from thorium in 1900, and in the course of the next two years he and Professors Ramsay and Soddy showed that the α-rays given off by thorium, radium, and several other radioactive elements are the rare gas helium in an electrified state. In fact, the α-radiation is a stream of α-particles, and each α-particle is a helium atom with two positive charges of electricity. Helium has an atomic weight of 4, and when the radium atom loses an α-particle and forms niton (radon), the atomic weight, which was 226, becomes 222. When niton in its turn loses an α-particle, the atomic weight drops to 218, that of the new element radium-*A*. Radium-*A* then loses an α-particle and forms radium-*B*, which turns into radium-*C*, and after a few more changes it is converted into a variety of lead with an atomic weight of 206.

The relationship of these elements to uranium is easy to explain. Uranium, an element of the same family as tungsten, molybdenum, and chromium, has an atomic weight of 238. Unlike many of the radioactive elements, it has been prepared in reasonable quantities, and has been known for very many years. It undergoes a slow change, half of its substance being converted in about five thousand million years to a new element called uranium-*X*; uranium-*X* loses a β-particle, which is an electron, and then another β-particle; in this way it becomes a new element called Uranium II, which is chemically indistinguishable from the original uranium. It has an atomic weight of 234; from this Uranium II are descended ionium, polonium, radium, and other elements, including three varieties of lead. So from thorium is descended another set of elements, including two more varieties of lead. These changes are illustrated by the following diagrams and we need not describe them in detail.

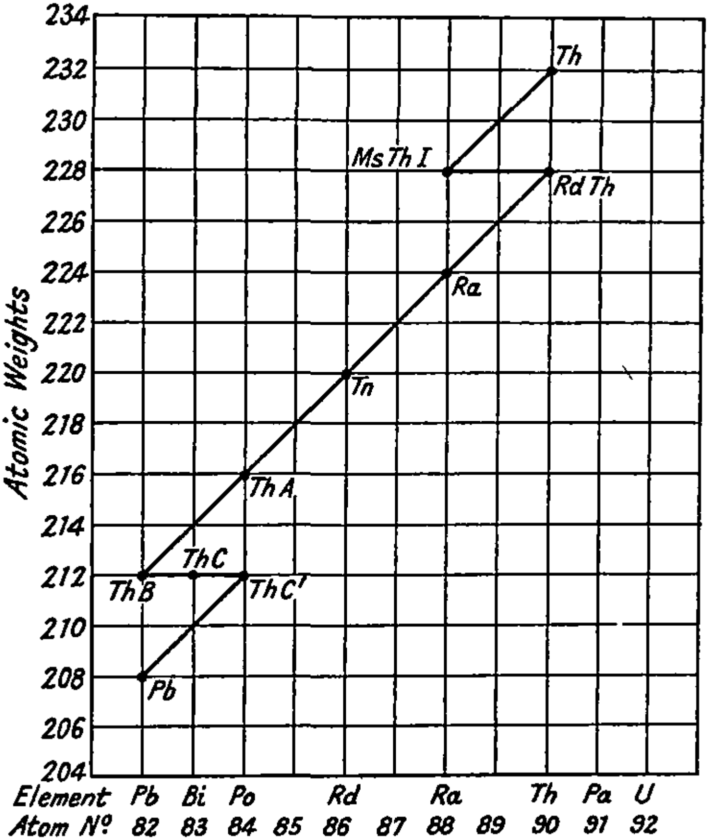
It was a startling thing for chemists to find that they were expected to believe that there were five varieties of lead that had exactly similar chemical properties but had atomic weights of 206, 208, 210, 212, and 214 respectively.

This was opposed to all their traditions, but they had to swallow this and much more. In some places lead was found associated with uranium, and it had an atomic weight of about 206·5, whereas ordinary lead has an atomic weight of about 207·1. Professor Soddy studied a number of radioactive substances that had similar chemical properties but different atomic weights, and he gave them the name "isotopes" in 1910. Then came J. J. Thomson



Changes in Uranium Series.

of Cambridge, who told us at the end of 1912 that neon existed in two varieties, one with an atomic weight of 20 and the other with an atomic weight of 22 (Plate IV). This sort of work was sadly interrupted by the war; chemists and physicists were occupied by other investigations until peace came in 1918.



Changes in Thorium Series.

All atoms contain electrons, and when a chemical substance is so treated that cathode rays are produced from it, the electrons that formed part of the atom are ejected in one direction and the remainder of the atom recoils in the other direction. In this way it is possible to obtain a stream of particles that are atoms which have lost one or more electrons, and so they are positively charged with electricity. They can therefore be diverted from their direction by an electric or a magnetic field. This field can pull the particle out of its straight path, just as the force of gravity pulls down a bullet discharged from a gun-barrel, and in each case a parabolic curve results. The amount of deflection depends partly on the electric charge of the particle and partly on its mass, and by taking proper measurements it is possible to calculate the mass of such a particle with an accuracy greater than one part in 1000. Dr. Aston of Cambridge devised a very ingenious instrument, called a mass spectrograph, for determining the mass of the atom of an element; this is a more accurate instrument than the original one that produced parabolas; the accuracy of the mass spectrograph is about one part in 10,000 (see Plate IV). Since the year 1918 Dr. Aston has investigated almost all the elements, in order to discover the mass of their atoms. Some of the elements show only one line on the recording apparatus; they have therefore only one species of atom. Among such elements are: aluminium, with a mass (atomic weight) of 27; arsenic, with a mass of 75; phosphorus, with a mass of 31; and sodium, with a mass of 23.

Some elements show two lines, and they consist of two varieties or isotopes with atoms of different masses. Among such are: calcium, with two isotopes with masses (atomic weights) of 40 and 44 respectively; iron, with isotopes with masses of 54 and 56; potassium, with isotopes 39 and 41; and nitrogen, with isotopes of 14 and 15, the latter being present in a very small proportion.

Some elements consist of many isotopes; thus cadmium has isotopes whose masses are 114, 112, 110, 113, 111, and 116, the most abundant one being the first, and the least abundant the last. Tin has isotopes of masses 120, 118, 116, 119, 117, 124, 122, 121, 112, 114, 115, in the order of their abundance; the first being the most abundant. Mercury has seven isotopes, lead has eight, bismuth fourteen, thallium eight.

At last, after a century of speculation about atomic weights, we know that in many cases the atomic weights are merely the average of the weights of the different isotopes.

This was, indeed, foreseen as a possibility by Crookes so long ago as the year 1888, but his notion was not supported by any experimental evidence, and it seemed then to be very improbable. In his Presidential Address to the Chemical Society in that year he said: "It does not necessarily follow that the atoms shall all be absolutely alike among themselves. The atomic weight which we ascribe to yttrium therefore merely represents a mean value around which the actual weights of the individual atoms of the 'element' range within certain limits. But if my conjecture is tenable, could we separate atom from atom we should find them varying within narrow limits on each side of the mean." Crookes's conjecture has been proved to be correct, but he was unfortunate in his choice of an element to illustrate it, for yttrium happens to be one of the few elements that is not a mixture of isotopes. There is only one kind of atom of yttrium, and it has a mass or weight of 89.

Of the many isotopes, one of the most interesting is the isotope of hydrogen, with an atomic weight of 2. Its discovery shows a certain amount of similarity to the discovery of argon. Aston showed by careful measurements with his mass-spectrograph that the ratio of the mass of the oxygen atom (allowing for the oxygen isotopes) to the mass of the hydrogen atom was 16 : 1·00756; on the other hand, the ratio of the atomic weights of oxygen and hydrogen as determined by chemical methods was 16 : 1·00777; this ratio was supposed to be accurate within about 0·00002. The discrepancy between these two ratios was sufficient to encourage Professor Urey of New York and his colleagues, Brickwedde and Murphy, to look for a heavy isotope of hydrogen, and they found it in 1932. It is called " deuterium." Heavy hydrogen is one of the most startling discoveries of the last twenty years, for it differs much more from the well-known isotope of hydrogen with the atomic weight of 1 than an isotope of any other element differs from its brother isotopes. The reason for this is that, whereas the isotopes of tin, for instance, differ from each other in mass by about 1 per cent., the atomic weight or mass of deuterium is twice that of the ordinary hydrogen. So we find that although deuterium will form a great many of the compounds that hydrogen does—perhaps all the compounds—it forms them more slowly, and the compounds so formed are themselves more lethargic than those of hydrogen.

Ordinary water contains about one part in 4000 of water in which two atoms of deuterium, instead of hydrogen, are united to one atom of oxygen. If we subject ordinary water to electrolysis, the deuterium oxide, " heavy water," is not electrolysed so quickly as the remainder, and so it tends to accumulate in the part not decomposed. By repeating this process a few times we can obtain water containing a large proportion of " heavy water." This is now manufactured regularly, and it is being used a good deal as a chemical agent in preparing certain new compounds. It is possible to replace one atom of hydrogen in an organic acid by one atom of deuterium and to trace this atom, or perhaps the group of which it forms a part, through a series of several different chemical changes. Very likely this method of labelling a particular atom and tracing its progress will be a powerful weapon in the hands of the chemist.

Heavy water is so slow in its action that some small animals—tadpoles, for instance—soon die in water if the proportion of " heavy water " is considerable.

Lewis and Macdonald by electrolytic condensation methods have now been able to make considerable quantities of practically pure " heavy water " with a density of 1·11. A still heavier isotope of hydrogen with an atomic weight of 3 seems to exist, but nothing is known about it.

There is also an isotope of helium with an atomic weight of 3. Of this also nothing is known except its existence.

CHAPTER XII

WHAT IS AN ATOM?

When we look back to the first ten or twelve years of this century, we realize that such a mass of new and interesting information had been recently published that more new discoveries were certain to be made. Almost every new discovery in chemistry and physics opens up a new possibility of exploring into the unknown. Many new tools had been placed in our hands that had previously not been available; there was the new *X*-ray photography; there were the new radioactive elements, continuously emitting sundry kinds of radiation; there was the recent work of J. J. Thomson on electrons; there were the new inert gases. There was also another factor to be considered: a young professor named Rutherford who was destined to achieve great things. When we say he was destined, we mean that he had good brains, great industry, that touch of genius that makes one first-class man surpass his associates, and the power of selecting and inspiring a team of workers of exceptional ability. In these respects he is a worthy successor at Cambridge to another great man, Sir J. J. Thomson.

The work on the structure of the atom at Cambridge has been one of the greatest scientific developments in the history of science; much excellent work was done elsewhere—in France, Germany, Scandinavia, and America—but in none of these countries was there so continuous and so great a volume of first-rate research on this subject as at the Cavendish Laboratory at Cambridge. The work was of two kinds: one purely mathematical—the new wave-mechanics—the other purely experimental—and both branches of work proceeded in co-operation with each other. The experimental work was facilitated by a clever little instrument, the spinthariscope, invented by the late Sir William Crookes shortly after radium was discovered by Professor and Mme. Curie. The spinthariscope is a screen covered by a phosphorescent substance; near this screen is a speck of radium, and there is a lens through which the screen can be observed. The speck of radium is always giving off α-particles, and as each one of these strikes against the phosphorescent screen there is a tiny flash of light that can be seen through the lens. The α-particles are incredibly small: their diameter is less than a hundred-millionth of an inch. Very much larger particles are quite invisible even with the help of the most powerful microscope. But with the spinthariscope, although you cannot see the particle, you can easily see the disturbance it makes, and you can count how many flashes there are in a minute and how the rate alters under different conditions. Another very clever process was invented by Professor C. T. R. Wilson, of Cambridge, to enable the track of an α-particle to be rendered visible and to be photographed. When an α-particle flies through a gas, it knocks off an electron every now and then from the many molecules which are in, or get in, its way. It is a matter of common knowledge that a fog or mist consists of a multitude of tiny drops of water condensed round a speck of dust or some such object. Moreover, if the air is suddenly cooled, there is a greater tendency to form fog or mist. Wilson passed α-particles through a gas that contained a little moisture; he cooled the gas by allowing it to expand; a mist formed along the path of the α-particle, consisting of the tiniest drops of water that collected round the loose electrons. A beam of light illuminated the drops so that they could be seen and be photographed (see Plate V, p. 166).

More than one physicist had speculated on the possible structure of the atom from a consideration of its electrical properties, among others Nagaoka, Lodge, J. J. Thomson, Kelvin, and Larmor. But Rutherford, by considering the scattering of the α-particles when they encountered the surface of a solid body, was able to do more than speculate: he was able to prove that the scattering of the α-particles in the particular way that was observed was due to the presence of some extremely tiny but heavy bodies existing in the solid surface, and that these bodies had large electric charges on them. It was well known at that time—the year 1911—that the electrons had some share or place in the atoms, and it was very probable that the atoms consisted of a nucleus that was positively charged with electricity, and a number of electrons outside that had the effect of making the atom as a whole electrically neutral. From about 1906 until 1911 Rutherford and his co-workers watched their α-particles, counted them, and after Wilson's method became available, photographed them. Geiger and Marsden, and C. G. Darwin, in 1909 and 1910 also did some valuable work in connexion with the scattering of α-particles.

Barkla, whose discovery of the *K* and *L* series of *X*-radiation has already been referred to, showed in 1911 that a study of α-particles indicated that the total number of electrons in any atom was about half the atomic weight, and in the same year van den Broek suggested that the positive charge on the nucleus, which is equal to the number of electrons, increased by one unit as the elements are traced along the periodic table. This notion seemed to be more probable when, in the next year, Moseley published his work on the *X*-ray spectra. Barkla and Moseley were both workers at Cambridge. Rutherford was a student at Cambridge, trained by J. J. Thomson. He was professor of physics at McGill University in Canada from 1898 until 1907. He then became professor at Manchester University, where he and his assistants, Bohr, Andrade, Geiger, Marsden, Darwin, and others, investigated the structure of the atom. Later, in 1919, he succeeded J. J. Thomson as Cavendish professor at Cambridge. Bohr in 1913 published an important theory dealing with the electrons and their position in atoms. Rutherford and Bohr conceived the atom as a minute heavy nucleus that was positively charged, and around this there existed a number of electrons in shells (energy levels). If the nucleus has a positive charge of 10, there will be ten electrons in the shells, each being equivalent to a negative charge of one unit, so the whole atom will be electrically neutral. The Rutherford–Bohr atom will have an additional positive charge on the nucleus and an additional electron in the shells for each step along the periodic table, and about this time the habit grew up of arranging elements in their atomic numbers—that is, places in the periodic table—rather than in the order of their atomic weights.

In 1916 Kossel, and G. N. Lewis independently, referred to the fact that the inert gases were very stable, and they attributed this stability to the fact that these gases had, with the exception of helium, an outer ring of eight electrons. They showed that if it was assumed, as Rutherford and Bohr did, that the valency of an element depended on the number of electrons in the outside ring or shell, then many stable compounds were formed by the union of an element having seven such electrons with an element having one such. Other compounds are formed by an element having six external electrons and one with two external electrons, and both Kossel and Lewis brought forward a good deal of evidence to show that the union of two elements so as to complete an external shell of eight electrons was a normal and satisfactory way of making stable compounds.

As no element has a higher valency than eight, it seemed obvious that when an element has more than eight electrons, these will be contained in more than one shell. J. J. Thomson determined the mass of an electron; it is quite immaterial by comparison with the mass of an atom—even a score or eighty electrons have no weight that is worth bothering about. The weight of the atom of hydrogen or any other element is to all intents and purposes concentrated in the very minute nucleus.

We assume that the hydrogen atom has a minute nucleus with a weight of 1 and an electron a little distance away from the nucleus.

The next element is helium; it has a nucleus four times as heavy as that of hydrogen, and it has two electrons. For some reason that is not very easy to understand or explain, it does not possess a valency of two, but it has no valency. The next element, lithium, has, not a valency of three, but of one. We must, for electrical reasons, attribute the chemical activity of an element to the outermost of the electrons, and so we conclude that in lithium we have a nucleus weighing seven times as much as the hydrogen nucleus, then a ring of two electrons and an outer electron that is responsible for the monovalency of lithium. The whole of the group of elements of which lithium is the first element can be represented by the first table on p. 147.

The weight of the nucleus of these elements is twice the atomic number, sometimes with an extra unit. It was pointed out in an earlier chapter (see p. 59) that only a part of the weight of the atom is concerned with holding the electrons in equilibrium, and so is indirectly responsible for the chemical activity of the element; the remainder of the nucleus is, in this sense, chemically inert; lithium, beryllium, boron, and fluorine each contain one unit of such inert matter. This is the interpretation which the authors put on the diagram on p. 58 and on the atomic weights of the elements, but other interpretations are possible. Our knowledge of the nucleus of the atom is steadily growing, but is not very definite. Possibly all the matter in the nucleus of an atom is chemically inert.

Element.	Atomic Number.	Weight of Nucleus (Atomic Weight).	Number of Electrons.	
			Inner	Outer.
Lithium . .	3	7	2	1
Beryllium .	4	9	2	2
Boron . .	5	11	2	3
Carbon . .	6	12	2	4
Nitrogen .	7	14	2	5
Oxygen . .	8	16	2	6
Fluorine . .	9	19	2	7
Neon . .	10	20	2	8

The next group of elements can be similarly represented by the following table:

Element.	Atomic Number.	Weight of Nucleus.	Number of Electrons.		
			Inner & Middle.		Outer.
Sodium .	11	23	2	8	1
Magnesium .	12	24	2	8	2
Aluminium .	13	27	2	8	3
Silicon .	14	28	2	8	4
Phosphorus .	15	31	2	8	5
Sulphur .	16	32	2	8	6
Chlorine .	17	35·5	2	8	7
Argon . .	18	40	2	8	8

Here also, and in all the subsequent elements, the atomic weight (weight of nucleus) is twice the atomic number, sometimes with the addition of a few units.

This table requires little explanation; the only new feature is the fractional character of the weight of the chlorine nucleus. Just as there are different varieties of lead with the same chemical properties but with different atomic weights, so, as Soddy suggested and as Aston proved, chlorine consists of two isotopes; they are indistinguishable chemically, but one variety has an atomic weight of 35, and the other has an atomic weight of 37. In all chlorine that occurs in nature these two isotopes are mixed together in the same proportion, and the average atomic weight is 35·457.

In the next group the electrons are arranged as follows:

Element.	Atomic Number.	Weight of Nucleus	Number of Electrons.	
			Inner & Middle.	Outer.
Potassium	19	39·1	2 8 8	1
Calcium	20	40 1	2 8 8	2
Scandium	21	45	2 8 8	3
Titanium	22	47·9	2 8 8	4
Vanadium	23	50 9	2 8 8	5
Chromium	24	52	2 8 8	6
Manganese	25	55	2 8 8	5 2
Iron	26	55 8	2 8 8	6 2
Cobalt	27	59	2 8 8	7 2
Nickel	28	58·7	2 8 8	8 2

In this group we notice that the outer shell of electrons gradually increases from 1 to 10, and in order to adhere more or less to the rules, the shell of outer electrons is subdivided by chemists in a way that fits in quite well with the *X*-ray spectra of the elements in this group. The elements scandium, vanadium, manganese, and cobalt are either elements that exist as single isotopes or, if one of these has more than one isotope, then all the other isotopes are present in an insignificant quantity.

The other elements in this group are all mixtures of isotopes.

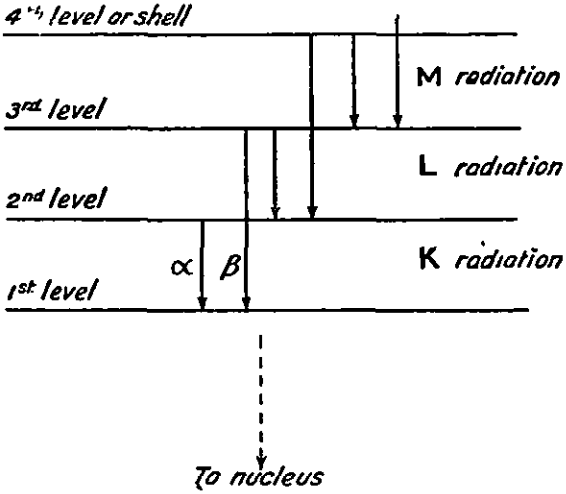
Iron, cobalt, and nickel have valencies that are sometimes 2 and sometimes 3. When iron is bivalent, we believe that the outer electrons, eight in number, are in two shells, six in one shell and two outside the others. When iron is trivalent, we believe that the outer electrons are five in one shell and three outside the others. Similar explanations are given of the valencies of cobalt and nickel.

The next group has electrons as follows:

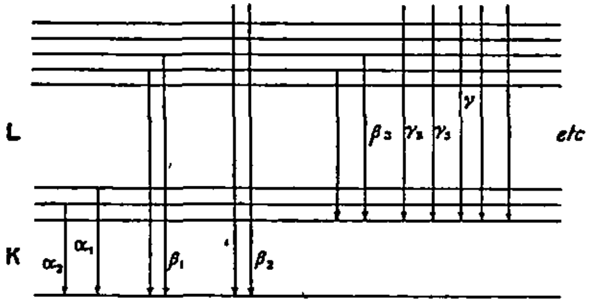
Element.	Atomic Number.	Weight of Nucleus.	Number of Electrons.				
			Inner & Middle.			Outer.	
Copper	29	63·5	2	8	8	10	1
Zinc	30	65 3	2	8	8	10	2
Gallium	31	69·9	2	8	8	10	3
Germanium	32	72 5	2	8	8	10	4
Arsenic	33	74·9	2	8	8	10	5
Selenium	34	79 2	2	8	8	10	6
Bromine	35	79 9	2	8	8	10	7
Krypton	36	82·9	2	8	8	10	8

If we consider the various energy levels in which the electrons occur, we must remember that if the element is bombarded by cathode rays (electrons) so as to emit *X*-rays, the electrons will have an additional energy given to them, and they escape from their usual places and are driven farther away from the nucleus. On the return of the electrons to their normal positions they emit the *X*-ray spectrum. An element like copper has five great shells in which the electrons normally live, and we may number these, number 1 being the innermost shell of two electrons, the next being one of eight electrons, and so on, ending with one outer electron all by itself.

Electrons may be driven, by a suitable cathode-ray bombardment or by other means, from one shell to the next outer one, or the next but two, or even farther. In due course the electron or some other one will return to the inner shell. An electron returning to fill up a gap in the innermost shell will give rise to the *K*-radiation; an electron returning to fill up a gap in the next shell causes the *L*-radiation; an electron returning to the third shell gives the *M*-radiation. And the different lines in the *K*-radiation denote returning electrons coming from different shells. We can now see why it is that the *L*-radiation of *X*-rays cannot be detected in the atoms with low atomic numbers, and that only atoms with high atomic numbers give the *M*-radiation.



The true position is even more complicated than this simple explanation. We have shown only two lines in the *K*-radiation; there may be as many as six; we have shown only two lines in the *L*-radiation and there may be as many as twenty-two. The explanation is that there are layers in each shell, and an electron returning from one layer gives a different line in the *X*-ray spectrum from an electron returning from another layer. Our diagram should be more like this:



Turning to the next column in the table, we find, from a study of *X*-ray spectra as well as from purely chemical considerations, that the electrons will be placed as in the following table:

Element.	Atomic Number.	Weight of Nucleus.	Number of Electrons.					
			Inner & Middle.				Outer.	
Rubidium .	37	85·4	2	8	18	8		1
Strontium .	38	87·6	2	8	18	8		2
Yttrium .	39	88·7	2	8	18	8	1	2
Zirconium .	40	90·6	2	8	18	8	2	2
Columbium .	41	93·1	2	8	18	8	4	1
Molybdenum	42	96	2	8	18	8	5	1
Masurium .	43		2	8	18	8	6	1
Ruthenium .	44	101·7	2	8	18	8	7	1
Rhodium .	45	102·9	2	8	18	8	8	1
Palladium .	46	106·7	2	8	18	8	4	6

It will be noticed that the proportion of inert matter in the atom increases as we proceed along the periodic table. Rubidium has an atomic weight of 85·44, of which 74 belongs to the active material and the remaining 11·44 is inert. Rubidium is a mixture of two isotopes of atomic weights, or masses, of 85 and 87 respectively. Molybdenum, with an atomic weight of 96. is a mixture of

Element.	Atomic Weight.	Weight.	Number of Electrons.						
Silver	47	107·8	2	8	18	18	1		
Cadmium	48	112·4	2	8	18	18	2		
Indium	49	114·8	2	8	18	18	3		
Tin	50	118·7	2	8	18	18	4		
Antimony	51	121·7	2	8	18	18	5		
Tellurium	52	127·5	2	8	18	18	6		
Iodine	53	126·9	2	8	18	18	7		
Xenon	54	130·2	2	8	18	18	8		
Cæsium	55	132·8	2	8	18	18	8	1	
Barium	56	137·3	2	8	18	18	8	2	
Lanthanum	57	138·9	2	8	18	18	8	1 2	
Cerium	58	140·2	2	8	18	19	8	1 2	
Praseodymium	59	140·9	2	8	18	20	8	1 2	
Neodymium	60	144·2	2	8	18	21	8	1 2	
Illinium	61		2	8	18	22	8	1 2	
Samarium	62	150·4	2	8	18	23	8	1 2	
Europium	63	152	2	8	18	24	8	1 2	
Gadolinium	64	157·2	2	8	18	25	8	1 2	
Terbium	65	159·2	2	8	18	26	8	1 2	
Dysprosium	66	162·5	2	8	18	27	8	1 2	
Holmium	67	163·4	2	8	18	28	8	1 2	
Erbium	68	167·7	2	8	18	29	8	1 2	
Thulium	69	169·4	2	8	18	30	8	1 2	
Ytterbium	70	173·6	2	8	18	31	8	1 2	
Luteciam	71	175	2	8	18	32	8	1 2	
Hafnium	72	178·6	2	8	18	32	8	2 2	
Tantalum	73	181·5	2	8	18	32	8	3 2	
Tungsten	74	184	2	8	18	32	8	4 2	
Rhenium	75		2	8	18	32	8	5 2	
Osmium	76	190·8	2	8	18	32	8	6 2	
Iridium	77	193·1	2	8	18	32	8	7 2	
Platinum	78	195·2	2	8	18	32	8	8 2	
Gold	79	197·2	2	8	18	32	8	10 1	
Mercury	80	200·6	2	8	18	32	8	10 2	
Thallium	81	204·4	2	8	18	32	8	10 3	
Lead	82	207·2	2	8	18	32	8	10 4	
Bismuth	83	209	2	8	18	32	18	10 5	
Polonium	84		2	8	18	32	18	10 6	
	85		2	8	18	32	18	10 7	
Niton	86	222	2	8	18	32	18	10 8	
	87		2	8	18	32	18	10 8	1
Radium	88	225·9	2	8	18	32	18	10 8	2
Actinium	89		2	8	18	32	18	10 8	1 2
Thorium	90	232·1	2	8	18	32	18	10 8	3 1
Protoactinium	91		2	8	18	32	18	10 8	4 1
Uranium	92	238·1	2	8	18	32	18	10 8	5 1

isotopes, whose weights or masses are 98, 96, 95, 92, 94, 100, and 97 in the order of their relative abundance, the 98 isotope being the most abundant. The active weight of molybdenum is 84, twice the atomic number, and so on with the other elements.

The remaining elements present the same general features as those we have already considered, and we will include them all in one table (see p. 152).

The long list of the rare-earth elements from Lanthanum to Lutecium is a singular one. All these elements are trivalent, and have three outer electrons, one and two others. The number of electrons in the adjoining shell increases from 18 up to 32, but these electrons do not affect the valency. At last we have an explanation of this singular group of rare-earth elements which resemble each other so closely and have puzzled chemists for seventy years.

Although the number of external electrons determines the valency of an element, the attraction binding several atoms together in a molecule cannot always be expressed so simply. Hydrogen has one external electron and is monovalent, but in some compounds it seems that a hydrogen atom is kept in place and attracted by two other atoms, not one. It is to a certain extent not a question of the total amount of attraction available, but of how to split up or share the attraction; we know that a man with £4 can share his assets with three others; he can also share it with four others. We must in some cases admit fractional parts of valency, just as we admit fractional parts of a pound. In some molecules we must admit the fractions even if we do not know exactly what the fractions are, and even if we cannot draw lines on a diagram to represent them.

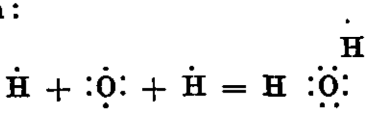
CHAPTER XIII

CHEMICAL ATTRACTION

It has, we think, been established at last, after more than a hundred years of investigation in a scientific way, that chemical combination is caused by, or is identical with, the electrical attraction that exists between the electrons outside the nuclei of the elements concerned and the various nuclei themselves, and that the principal electrons to take part in this phenomenon are those in the outer sphere or level of electrons.

There is a good deal of evidence to prove that an outer sphere or level of eight electrons is usually complete, and that an atom with eight electrons in the outer shell will not display great chemical activity. Let us see how chemists interpret chemical combination on this basis, and let us, if we can, try to remember always whether we are considering gaseous, liquid, or solid substances, for statements made about one of these may not be true of the others.

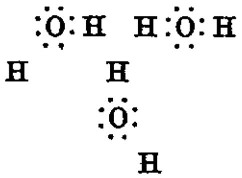
Water in the gaseous state—that is, steam—consists of individual molecules of H_2O, formed in the following way: oxygen consists of a nucleus with six electrons in its outer shells, always ready and willing to attract two more electrons into their orbit. The hydrogen nucleus has one solitary electron, and we believe that what takes place may be denoted with a fair measure of accuracy by this diagram:



$$\dot{H} + :\underset{\cdot}{\dot{O}}: + \dot{H} = H\ \begin{matrix}\dot{H}\\ :\underset{\cdot\cdot}{\ddot{O}}:\end{matrix}$$

The letters denote the nuclei and inner electrons, the dots denote the electrons in the outer shells.

In liquid water we must conceive more complicated compounds, perhaps of this nature :



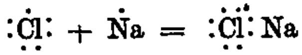
We do not believe that water consists of a number of molecules separate from each other, whether the molecules are H_2O, or H_4O_2, or H_6O_3. We believe that in the liquid each HOH group will be surrounded by four similar groups placed round the first one in such positions as the angles of a tetrahedron are placed round its centre. These four groups are chemically but loosely combined with the first group and with each other and with any other adjacent HOH groups.

We must not regard the groups as either fixed or stationary; they are in constant but irregular movement and they are always losing an atom or a group of atoms and being joined by other wandering groups. These wandering groups are not molecules, and the smaller groups that wander more easily between the larger ones are electrically charged; we suppose that there are wandering groups of the nature of H_3O, H_3O_2, H_2O_2 and very likely still larger groups. In solid ice there is a small movement of the atoms possible, but the structure is nevertheless a closely-packed one; in steam the separate molecules are at considerable distances from each other. Water is much more nearly the density of ice than of steam, and we therefore suppose that the atoms or groups of atoms in water are nearly closely-packed, but there is a considerable movement of these, and the hotter the water the greater the amount of movement.

Doubtless the details of the structure of liquid water vary with the temperature.

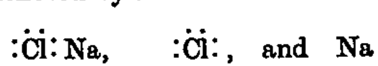
Ice is probably more complicated than liquid water; there is more than one variety of ice, more than one way in which the heavier oxygen nuclei are arranged in space. One variety of ice has its oxygen atoms arranged in hexagonal fashion, something like a set of benzene rings. We are not to consider ice as a series of flat, independent sections, but as an orderly arrangement in three dimensions, or lattices, in which twice as many hydrogen atoms as oxygen atoms are spread out in length, breadth, and thickness to form a solid mass, all of which is held together by the electrical attraction existing between the electrons and the nuclei of oxygen and hydrogen. The way in which the oxygen nuclei in ice lie in space has been calculated by Sir William Bragg and his son Professor W. L. Bragg, and by others, and is now well known; no one knows how the hydrogen nuclei are arranged, nor how the electrons are arranged, but it will probably be on a symmetrical basis that is capable of infinite extension in all directions. Moreover, the plan will usually have a hexagonal basis, for the usual crystals of ice are hexagonal.

Let us now consider common salt, NaCl; we may say that the vapour of common salt will be formed thus:



$$:\overset{\cdot}{\underset{\cdot\cdot}{\mathrm{Cl}}}: + \dot{\mathrm{Na}} = \;:\overset{\cdot\cdot\cdot}{\underset{\cdot\cdot}{\mathrm{Cl}}}:\mathrm{Na}$$

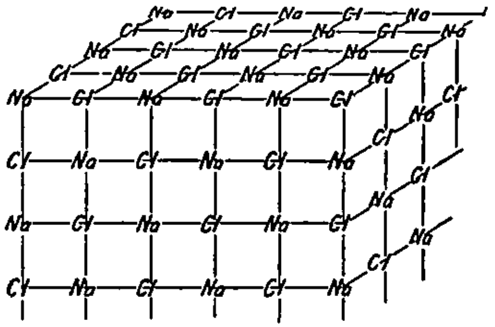
It is believed that a solution of salt will consist, wholly or partially, of water combined with or mixed with bodies that may be denoted by:



$$:\overset{\cdot\cdot}{\underset{\cdot\cdot}{\mathrm{Cl}}}:\mathrm{Na}, \qquad :\overset{\cdot\cdot}{\underset{\cdot\cdot}{\mathrm{Cl}}}:, \quad \text{and} \quad \mathrm{Na}$$

The proportions of these various bodies and the nature of the combination between them and the liquid water are largely a matter of conjecture. The proportions are believed to vary with the concentration of the solution, the temperature, and other factors. The exact nature of the chemical combination between the water and the sodium chloride, of the bits $:\!\underset{\cdot\cdot}{\overset{\cdot\cdot}{\mathrm{Cl}}}\!:$, and Na, commonly spoken of as the chlorine ion and the sodium ion, is not known, but is undoubtedly the attraction of the electrons to nuclei or groups of nuclei and electrons in the vicinity. We shall have to consider later the combination between water and other substances.

The solid crystal of common salt has a constitution that is easy to understand and to picture in our minds. It is based on a cubical system of symmetry extending in three directions, and we may denote a small piece of the system by this diagram. We must imagine a shell of eight electrons surrounding each chlorine nucleus and binding the whole structure together into a solid mass. We know nothing more about the manner in which the electrons are arranged, but guesses have been made, and sometimes names given to the guesses.



Common salt is as simple a chemical compound as exists; nevertheless it has taken a little time to explain the chemical combination, and we have shirked the explanation of the chemical combination that takes place when we dissolve salt in water.

Let us take two other substances, hydrochloric acid and ammonium chloride. The molecule of gaseous hydrochloric acid may be assumed to be formed thus:

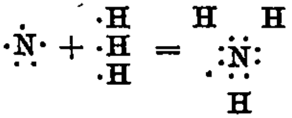
$$:\!\underset{\cdot\,\cdot}{\dot{\mathrm{Cl}}}\!: + \cdot\mathrm{H} = :\!\underset{\cdot\,\cdot}{\ddot{\mathrm{Cl}}}\!:\mathrm{H}$$

but this formula presents difficulties too abstruse to be explained here. The authors of this book do not happen to know how liquid hydrochloric acid is built up; it does not seem to be built up on the same plan as common salt, although the solution of it in water behaves in some respects in the same sort of way that the solution of common salt does.

Solid hydrochloric acid exists, but has not been carefully studied. It may be assumed that the way in which it is built up will resemble chemically, and perhaps geometrically, the way in which common salt crystals are built up.

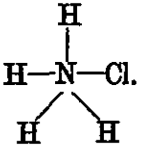
Now let us consider ammonium chloride; this is not stable in the gaseous state; when it is heated it breaks up into separate molecules of ammonia (NH_3) and hydrochloric acid (HCl).

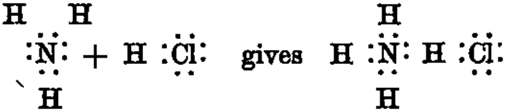
The molecule of ammonia will be formed thus:



$$\cdot\underset{\cdot\,\cdot}{\dot{\mathrm{N}}}\cdot + \begin{matrix}\cdot\mathrm{H}\\ \cdot\mathrm{H}\\ \cdot\mathrm{H}\end{matrix} = \begin{matrix}\mathrm{H} & & \mathrm{H}\\ & :\!\underset{\cdot\,\cdot}{\ddot{\mathrm{N}}}\!: & \\ & \mathrm{H} & \end{matrix}$$

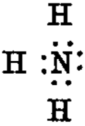
The molecule seems, from various characteristics, to be a pyramid with the nitrogen nucleus at the top, the three hydrogen nuclei forming the corners of an equilateral triangle at the base of the pyramid.

Both hydrochloric acid and ammonia have a complete outer shell of eight electrons; nevertheless they can combine together to form a new compound—the solid ammonium chloride. This is not exceptional, it is very common for such compounds to combine together, though elements with an outer shell of eight electrons are usually inactive. Fifty years ago or less it was usual to consider nitrogen as pentavalent and to denote ammonium chloride by a structural formula thus:  $\mathrm{H{-}\overset{\displaystyle H}{\overset{|}{N}}{-}Cl}$ with H H below. The modern view, for which there is a good deal of evidence, is that the compound should be explained thus:

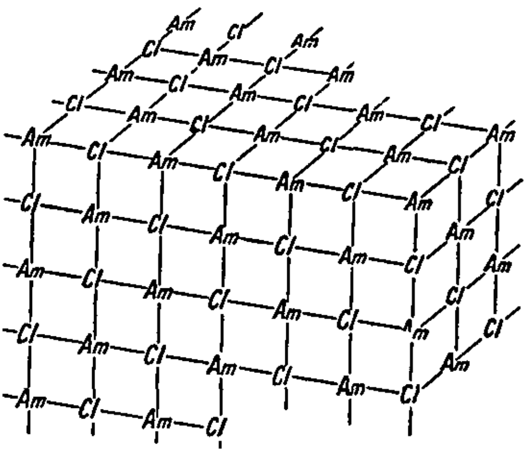


$$\begin{matrix}\mathrm{H} & \mathrm{H} \\ \multicolumn{2}{c}{:\overset{\cdot\cdot}{\underset{\cdot\cdot}{\mathrm{N}}}:} \\ \multicolumn{2}{c}{\mathrm{H}}\end{matrix} + \mathrm{H}\ :\overset{\cdot\cdot}{\underset{\cdot\cdot}{\mathrm{Cl}}}: \quad \text{gives} \quad \mathrm{H}\ :\overset{\displaystyle\mathrm{H}}{\overset{\cdot\cdot}{\underset{\underset{\displaystyle\mathrm{H}}{\cdot\cdot}}{\mathrm{N}}}}:\ \mathrm{H}\ :\overset{\cdot\cdot}{\underset{\cdot\cdot}{\mathrm{Cl}}}:$$

The nitrogen may be combined with the hydrogen thus:



$\mathrm{H}\ :\overset{\displaystyle\mathrm{H}}{\overset{\cdot\cdot}{\underset{\underset{\displaystyle\mathrm{H}}{\cdot\cdot}}{\mathrm{N}}}}:\ \mathrm{H}$ but the way in which the electrons are disposed in space is not entirely free from doubt. In any case it seems that the nitrogen nucleus will occupy the centre of a regular tetrahedron at the corners of which the hydrogen nuclei will be placed. The crystal of ammonium chloride will be represented thus:



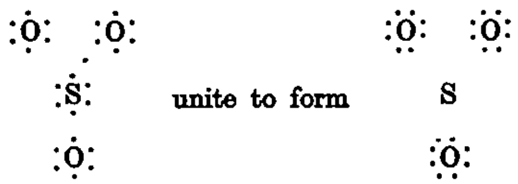
where Am denotes a tetrahedron at the centre of which is a nitrogen nucleus with four hydrogen nuclei at the corners. Each nitrogen nucleus and each chlorine nucleus will be surrounded by a shell of eight electrons binding the whole into a solid stable substance. The attraction between the various electrons and the various nuclei is what we call chemical combination.

Water, common salt, hydrochloric acid, ammonia, and ammonium chloride are simple substances that may be taken as types of an enormous number of chemical compounds; and whether we consider the molecules in the gaseous state or the aggregates that form the solid state, we shall find everywhere nuclei attached to other nuclei by shells containing, usually eight, electrons. Whether this is the only type of chemical compound, or whether there are different kinds of chemical combination, are questions that involve nice points of nomenclature and metaphysics, but these need not disturb us at the moment.

Let us consider another very simple substance, sulphuric acid, formed by the combination of sulphur trioxide and water.

Sulphur has six outer electrons, as oxygen has, and it can form a monoxide, a dioxide, and a trioxide.

The trioxide may be considered thus:

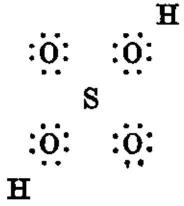


Three atoms of oxygen and one of sulphur.

One molecule of sulphur trioxide.

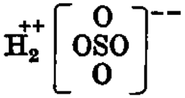
Each oxygen nucleus is surrounded by eight electrons, and you may assume, if you think fit, that the sulphur nucleus is also surrounded by eight electrons, for we do not know how the electrons in such an aggregate arrange themselves in space. You may, on the other hand, as many chemists do, suppose that the sulphur nucleus is surrounded by only six electrons and is thirsting for more. The difference between these conceptions is not very important, for on either assumption we can explain the existence of a combination of sulphur trioxide with water; water, as we know, consists of oxygen with an outer shell of eight electrons and two hydrogen nuclei in the offing.

The combination of SO_3 and H_2O will produce something of this sort, only not flat, and probably extending indefinitely in three dimensions:



We have not yet reached the limit of the compounds, for if we mix sulphuric acid with water, heat is evolved and a definite hydrate is formed, or in certain circumstances a mixture of definite hydrates. Exactly how these should be represented by such a diagram we do not know, but the chemical combination involved is of the same nature as the combination of sulphur trioxide and water. What happens when we dilute the liquid hydrate of sulphuric acid with more water is a complicated question to which no certain answer can be given. It is possible that the formation of such a dilute solution involves a consideration of changes that are not similar to the change that takes place when sulphur burns to form sulphur dioxide or when sulphur dioxide combines with oxygen to form sulphur trioxide, or when sulphur trioxide combines with water to form sulphuric acid.

The modern chemist, to save space, writes the formula of sulphuric acid thus:



$$\overset{++}{H_2}\left[\begin{matrix}O\\OSO\\O\end{matrix}\right]^{--}$$

instead of the old-fashioned structural formula $O_2S(OH)_2$, but these really are both conventional ways of representing the same arrangement in space. If we consider the spatial arrangement of perhaps half-a-dozen or ten nuclei and perhaps forty to eighty electrons, each with an attractive power that is not directed in a straight line, but in many or all directions, we shall not be surprised that we cannot devise simple rules that will be of universal application. The attractive power of one or two bodies may perhaps be so expressed, but there is a greater variety possible when we are dealing with a large number of centres of attraction. We must not be surprised, as people were in the middle of the nineteenth century, to find that a compound that seems to have no attractive power left unsatisfied may combine with another such compound. Nitrogen is sometimes divalent as in NO, sometimes trivalent as in NH_3, sometimes pentavalent as in N_2O_5, and rarely tetravalent as in NH_4, which has recently been found to be capable of an independent existence.

We are not sure, so complicated are the facts, that it is as easy to draw a hard-and-fast line to define chemical combination, or to separate a chemical compound from a mixture, as was supposed forty or twenty years ago. Mixed crystals are an instance; you may grow beautiful octahedral crystals of alum, an aggregate of potassium sulphate, aluminium sulphate, and water. But if you mix solutions of potassium sulphate, aluminium sulphate, and chromium sulphate together, you may obtain crystals in which you get a perfectly regular assembly of potassium, aluminium, chromium, sulphur, and oxygen nuclei all bound together in perfect order by scores of electrons. You have a mixture not only in the crystal, but also in a minute unit of the crystal. You have a mixture of aluminium and chromium sulphates, that can be varied indefinitely, and are we to say that there are an infinite number of chemical compounds of these crystals? This leads us to consider whether we call a crystal of alum a chemical compound or not; the alum does not exist in solution; in the crystal the potassium sulphate and the aluminium sulphate fit into some closely packed assembly in which there are spaces filled by molecules of water. The aggregate of these three forms octahedra, and we do not know whether the water is chemically united with the two sulphates, or is held by gravitation, or just fitted into what would have been empty spaces. Alum does not exist except in the crystalline state; if it is a chemical compound it is possibly one of quite a different nature from such a compound as hydrochloric acid, common salt, or benzene.

Contrary to the belief that has been held for many years, we are of the opinion that there is no sharp dividing line between a chemical compound and a mixture, and that there are so many examples of a strong chemical attraction and a weak one that we are justified in thinking that there is every gradation between the strongest chemical attraction and no attraction at all.

It seems to be impossible to state that any particular element has a definite combining power. What is the maximum valency of oxygen? There are compounds of oxygen in which one oxygen nucleus is united by electrons to four nuclei, but no one should be surprised to find a compound in which such a nucleus is so attached to five other nuclei.

The inert gases helium, neon, argon, krypton, and xenon should be incapable of taking part in chemical combination; they have a complete shell of outer electrons. Nevertheless they do possibly form a few not very stable compounds with water. The old notions that suggest that an element has arms like a man, a star-fish, or an octopus, ready to clutch some wandering atom, have been found to be not strictly in accordance with the facts. They were once useful, rough-and-ready guides; they are too rough for our modern refined methods. Nevertheless there is something in the general ideas of valency; they are still rough guides to the activity of the elements.

The fact that the attraction of an element is not always to be defined by a definite integer helps us to understand the structure of many compounds that are found in plants and animals. Some of these will be dealt with in later chapters.

CHAPTER XIV

BREAKING UP THE ATOM

WE have seen that in certain cases α-particles are expelled from a radioactive atom; in other cases β-particles or electrons are expelled. The evidence shows that these are expelled from the nucleus of the atom; whether they exist in the nucleus as α-particles and electrons, respectively, is not certain. It is also possible to drive off from an atom other bodies that may possibly be constituents of the nucleus; one of these is called the proton; it is a hydrogen atom positively charged. During the last four or five years three more bodies have been discovered which play a part in the structure of the atom or which can be driven off from it. One of these has a mass of very nearly 1 compared with a hydrogen atom, and is electrically neutral; this is called the neutron. Another—the positron—has, like the electron, a mass equal to $\frac{1}{1850}$ of the hydrogen atom; it differs from the electron because it has an opposite electric charge. The electron is a unit of negative electricity; the positron is a unit of positive electricity. The third body is derived from the atom of heavy hydrogen or deuterium; it is positively charged and has a mass of approximately 2, and is known as a deuton. The following table shows all these bodies:

Name.	Mass.	Electrical Charge.
α-Particle . .	4·0041	+ 2
Deuton . . .	2·0148	+ 1
Proton . . .	1·0081	+ 1
Neutron . .	1·0085	*none*
Electron . .	1/1850 = 0·00054	− 1
Positron . .	1/1850 = 0·00054	+ 1

The positron is rather a mystery; fifty years ago we were taught that there were two kinds of electricity, positive and negative; later this belief was abandoned and we were assured that there was only one kind of electricity, the negative electricity. Its unit was weighed and streams of it were subjected to all kinds of experiments. It was found to have the attributes of a vibration as well as those of a material particle, at any rate a particle possessing weight. We knew the electron thoroughly, and all the electrical phenomena we were acquainted with were capable of being explained on the assumption that a body had either enough electrons to keep it neutral, or a few extra electrons, in which case it was negatively electrified; or it lacked a few electrons, in which case it was positively electrified. No other unit of electricity was necessary or could be imagined. How could there be another unit capable of uniting with an electron and cancelling it? Obviously there could not be such a thing; it was like trying to believe that a man could have minus one (— 1) finger on each hand. And then somebody comes along and finds the positron; its path can be photographed; it can be bent out of a straight-line path by electricity or magnetism, but the bending is opposite to that of the electron (Plate V).

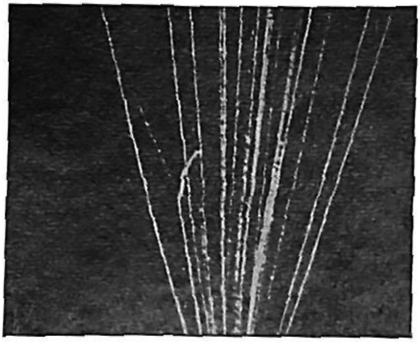
The positron is scarce and short-lived. The air has plenty of electrons in it and the first time a positron meets an electron they both disappear. The whole business is incredible; still, there are the tracks that have been photographed; we must pay attention to the evidence and interpret it as sensibly as we can. Robinson Crusoe, when he saw a solitary footprint in the sand, was not obliged to conclude that the man who made it had only one leg!

The neutron is just a little particle of matter; it has no chemical or electrical properties. It may account for all

TRACK OF AN α-PARTICLE [*C. T. R. Wilson.*

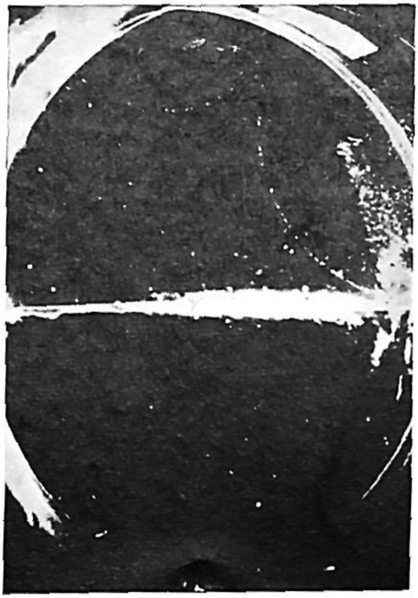
[*G. Shearer*

L-SPECTRUM OF



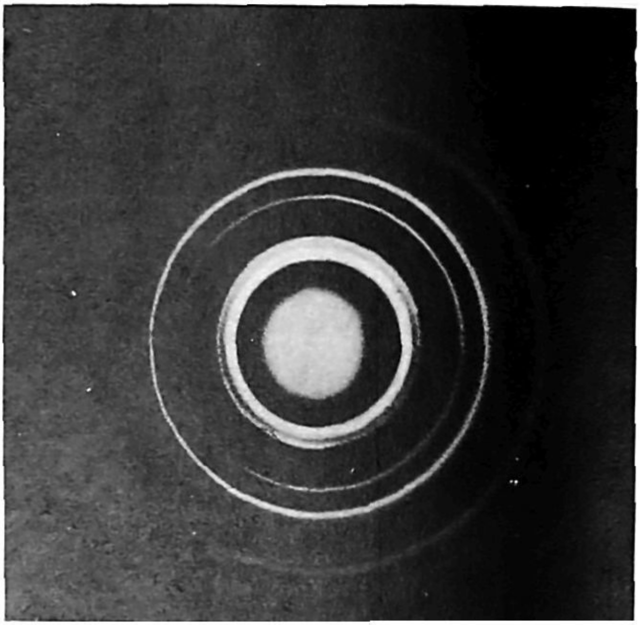
[*C. M. S. Blackett.*

DISINTEGRATION OF THE NITROGEN NUCLEUS BY α-PARTICLES



[*J. Chadwick, P. M. S. Blackett, and G. Occhialini.*

TRACK OF A POSITRON



[G. P. Thomson.

DIFFRACTION OF ELECTRONS BY A METAL FILM

[G. I. Finch.

PATTERN FROM SILICON CARBIDE, AFTER REMOVAL OF THE AMORPHOUS SKIN FROM THE SURFACE the inert matter contained in the chemical atoms, but this is guessing without the necessary evidence.

We may regard the deuton as a coalescence of a proton and a neutron; there is a certain amount of speculation permissible about such matters and not much strict proof. The mass of a proton plus the mass of a neutron is 2·0166, but the mass of the deuton is only 2·0148, and we believe that if a proton combines with a neutron, a small amount of mass—*i.e.*, 0·0018—is converted into energy. So, too, the α-particle is formed by the union of four protons; the mass of these is 4 × 1·0081 or 4·0324; but the mass of the α-particle is only 4·0041, and the difference between these two masses has been converted into energy.

Although we do not know very much about the constitution of the nucleus, and are obliged to make guesses, there is no doubt whatever about the existence of the six bodies mentioned in the table. We know how to produce them, we can photograph the tracks of those which are electrically charged, and we can measure very accurately the masses of them all. The radioactive elements emit α-particles and electrons which travel at a high speed. By means of expensive machines weighing many tons, it is possible to produce enormous voltages and to project deutons and protons against a substance, and to observe and photograph the ways in which the atoms are broken up or altered. It is also possible by simple devices to make insignificant amounts of many interesting elements and particles.

In this way it is possible to change one atom into another atom, and to make sometimes stable new atoms and in other cases unstable—that is, radioactive—atoms that may persist for a few seconds, a few days, or longer. The quantities of these new atoms are extremely minute and the cost of the manufacture may be very great; there is no likelihood of our being able to convert a few ounces of one metal into another. Among the bodies that are used for bombarding an element so as to convert it into another, the best is the neutron; the other bodies are all electrically charged and easily diverted from their paths by the nuclei of the element. They have consequently only a small power of penetration; the neutron has no charge and a very great power of penetration. Neutrons are produced when beryllium and boron are bombarded by α-particles. The deuton also is an excellent projectile for bombarding an element, for it has only one electric charge, as the proton has, and is twice as heavy.

It is possible by such bombardment, in some cases to convert one isotope of an element into another isotope of the same element and to prepare isotopes that have not been hitherto known. Thus, if deutons (D) are bombarded against heavy hydrogen, a new isotope of helium is produced with a mass of 3, and at the same time a neutron comes into existence. The change may be represented as follows:

$$\underset{\text{mass 2.}}{\mathrm{D}} + \underset{\text{mass 2.}}{\mathrm{D}} \longrightarrow \underset{\text{mass 3.}}{\mathrm{He}} + \underset{\text{mass 1.}}{n}$$

It is also possible by the same process to prepare an isotope of hydrogen with a mass of 3. Lithium (the isotope of mass 7), if bombarded by protons, is converted into helium:

$$\underset{\text{mass 7.}}{\mathrm{Li}} + \underset{\text{mass 1.}}{\mathrm{H}} \longrightarrow \underset{\text{mass 8.}}{2\mathrm{He}} + \text{certain rays.}$$

Deutons projected against lithium convert it into helium with the formation of a neutron:

$$\underset{\text{mass 7.}}{\mathrm{Li}} + \underset{\text{mass 2.}}{\mathrm{D}} \longrightarrow \underset{\text{mass 8.}}{2\mathrm{He}} + \underset{\text{mass 1.}}{n}$$

Nitrogen bombarded by protons produces carbon and helium thus:

$$\underset{\text{mass 14.}}{\mathrm{N}} + \underset{\text{mass 1.}}{\mathrm{H}} \longrightarrow \underset{\text{mass 11.}}{\mathrm{C}} + \underset{\text{mass 4.}}{\mathrm{He}}$$

It will be noticed that the carbon produced is an isotope, with atomic weight 11, of the usual carbon, which has an atomic weight of 12. Nitrogen bombarded by deutons produces oxygen and neutrons :

$$\underset{\text{mass 14.}}{\mathrm{N}} + \underset{\text{mass 2.}}{\mathrm{D}} \longrightarrow \underset{\text{mass 15.}}{\mathrm{O}} + \underset{\text{mass 1.}}{n}$$

In this case the oxygen produced is an isotope of the element having an atomic weight of 15.

Aluminium bombarded by α-particles can yield (i) an isotope of phosphorus plus a neutron or (ii) an isotope of silicon plus a proton thus :

$$\underset{\text{mass 27.}}{\mathrm{Al}} + \underset{\text{mass 4.}}{\mathrm{He}} \longrightarrow \underset{\text{mass 30.}}{\mathrm{P}} + \underset{\text{mass 1.}}{n}$$

$$\underset{\text{mass 27.}}{\mathrm{Al}} + \underset{\text{mass 4.}}{\mathrm{He}} \longrightarrow \underset{\text{mass 30.}}{\mathrm{Si}} + \underset{\text{mass 1.}}{\mathrm{H}}$$

About a hundred such transmutations or changes are already known, the elements changed being hydrogen, lithium, beryllium, boron, carbon, nitrogen, oxygen, fluorine, sodium, magnesium, and aluminium.

It was Lord Rutherford who first broke up the atom and changed one element into another in this way.

> He broke up the indivisible,
> Made plain the invisible,
> Changed the immutable,
> And unscrewed the inscrutable.

In the year 1919 he began a long series of brilliant experiments by bombarding atoms of nitrogen with α-particles, and succeeded in dislodging protons and leaving a residue of carbon (Plate V). Now in many countries many workers are extending our knowledge of these singular transmutations.

In addition to the products of the disintegration of uranium, thorium, and protoactinium, two other elements have for several years been known to be feebly radioactive;

these are rubidium and potassium. It has been suggested that each of these elements is commonly accompanied by an unstable—that is, radioactive—isotope and that the radioactivity of rubidium and potassium is entirely due to the existence of these isotopes. Recent work by Joliot, Curie-Joliot, and other workers in several countries lends some confirmation to this suggestion.

It has been found that many elements when bombarded by neutrons become radioactive, usually for a brief time. This temporary radioactivity is often accompanied or caused by the liberation of an unstable isotope. Thus fluorine can be made to emit an isotope of oxygen with a mass of 19 which loses half its activity in less than a minute; it will also emit an isotope of nitrogen with a mass of 16 that is even more unstable. Aluminium emits during and immediately after such a bombardment an unstable isotope of aluminium with a mass of 28, an unstable isotope of magnesium with a mass of 27, losing half its activity in ten minutes, and an isotope of sodium with a mass of 24, losing half its activity in 15 hours. It is usual to call this period of 15 hours the half-life of the isotope in question.

Chlorine can be made to emit an isotope of phosphorus with a mass of 32 and a half-life of 14 days. Potassium will emit an isotope of potassium with a mass of 42 and a half-life of 16 hours. Similar actions result from the bombardment with neutrons of ruthenium, antimony, tellurium, erbium, tungsten, iridium, gold, and bismuth. Perhaps almost all the elements will in time be found to be capable of such artificial radioactivity.

We do not know how the nucleus of an atom is constructed. It used to be thought that it contained only protons and electrons, for these were the only known units, except the α-particle, and the latter could easily be supposed to be built up from protons. Since the discovery of neutrons, deutons, and positrons the old belief has been abandoned, and most people who have recently studied the question frankly admit that they know nothing of the structure of a nucleus; all they know is that the nucleus may emit under suitable conditions α-particles, protons, electrons, positrons, and other electrical radiations. Whether these exist in the nucleus normally, or whether they are only formed as they are emitted, is a matter on which there is no evidence.

CHAPTER XV

ELECTRON DIFFRACTION

ELECTRONS are small particles in an atom or collection of atoms; they are possibly moving rapidly in a very small orbit, usually occupying a position limited to some point on an ellipse outside the nucleus of an atom. It would be still more accurate, perhaps, to say that there are several imaginary shells outside the nucleus, and that an electron can occupy a position on any one of these shells, depending on temperature, pressure, and so forth. As these conditions alter, the electron may be forced onto an outer shell or onto an inner one, if there is an inner one. This is how we can think of an electron, and it may be that we should think of the ellipse not as an orbit, but merely as a locus, to use a mathematical phrase. A locus is a defined straight line or curve upon which a point—for instance an electron—may be placed, and it may not be placed outside the locus. The electron does not necessarily travel round this ellipse, but it cannot in a stable condition be anywhere except somewhere on the ellipse. There are also electrons that do not form part of any molecule, but fly through space at a prodigious speed. A flash of lightning is a huge collection of such electrons; *all currents of electricity are collections of* electrons. We cannot by any instrument see the electron, but we can follow its track in certain circumstances. A beam of electrons travelling through a space that contains a number of neutral particles may electrify these, and so cause chemical changes that can be recorded by photographic methods. Although it is not possible to see the electron, we can in this way identify its path. Some one compared this to the case of a man walking in a jungle; perhaps we cannot see him, but we can know where he is going by noticing the flocks of birds that fly away on his approach.

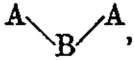
A beam of electrons travelling rapidly through space is, like a beam of light, characterized by two phenomena: in some respects the electron acts as if it were a small particle of matter; in other respects it acts as if it were a rapidly moving wave or impulse. A few years ago Prince L. de Broglie suggested that we should regard the electron, not as one or the other of these, but as both; it is a particle carried forward on a wave associated with it. Professor G. P. Thomson, a son of Sir J. J. Thomson, in 1928, and Davisson and Germer independently of him in the same year, showed that a beam of electrons, like a beam of any other waves, is capable of showing interference patterns comparable with those produced by *X*-rays and by light rays. If a beam of electrons is directed on to a very thin film of metal, the electron waves will be diffracted or reflected by the atoms or nuclei of the metal, and will form here and there shining points that can be photographed and interpreted. The electron particles must still be considered as tiny by comparison with an atom, but the waves that accompany them have a range or an influence larger than an atom. The front of such a wave, associated with one electron, will be wide enough to cover more than one atom; the length of the train of such a wave is much more (see Plate VI).

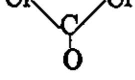
By passing a stream of electrons through a thin film of metal or through small crystals, and photographing the diffraction patterns, we can learn a good deal about the nature of the film or of the crystals. Analysis by means of *X*-rays is particularly useful for investigating the structure of the interior of objects; analysis by electrons is particularly useful for the study of the surface. During the last four or five years there has been much study by this method of the thin films that form on metals which are exposed to the air. Many metals speedily develop a thin film of oxide, which may be a great protection against any further corrosion; these films are often so thin that they cannot be analysed by chemical methods, but they can be analysed by electron diffraction, and new oxides of some of the common metals have been discovered in this way. Another research has recently been pursued in connexion with highly polished surfaces of some of the metals. The surfaces of many substances are often exceptionally chemically active, and their study is of great interest and some industrial importance.

The polishing of metals is very different from the cleaning of them; those who polish steel knives and silver spoons are well aware of this. Many of the older generation can recall happy hours spent in cleaning and burnishing steel bits, and stirrups, and scabbards, sitting in the open in glorious weather on Salisbury Plain or some other country suitable for cavalry manœuvres, while the horses, tethered in neat lines, munched their hay. It is easy to clean away the rust; a little fine emery-paper will easily remove rust, even of long standing, but it leaves a scratchy surface, not a burnished one. To get a beautiful smooth surface on steel—a far more beautiful surface than you can get on silver or nickel—you must rub long and hard, either with a steel burnisher or with a soft powder such as rouge. What is the change in structure brought about by such polishing or burnishing? The usual surface of a metal, steel, silver, or lead, is crystalline; the crystals may be large or small, but they exist and they give a dull surface on the whole. The effect of polishing, as was pointed out by Sir George Beilby sixteen years ago, is to drag away from their original positions small portions of the crystals and deposit them in new positions until the whole crystalline nature of the surface is replaced by an amorphous surface. A new skin is given to the metal, and this covers up the deep scratches that may have been visible and gives an absolutely uniform surface that reflects the light uniformly and shines so as to gladden the heart of man. The new skin may persist for months, but the atoms of the metal are not quite stationary; they move a little, and if the metal is heated, or hammered, or fatigued, they may move a good deal and gradually again form crystals. Beilby discovered the amorphous surface layer by examining it under a microscope, etching the surface with acids, and other processes. During the last four or five years the researches of Finch and others have shown that by electron diffraction the existence of the amorphous Beilby layer can be proved beyond question. A crystalline surface gives an entirely different electron diffraction pattern from that of an amorphous surface. By electron diffraction Finch showed that a very thin layer of a metal *A* deposited on a polished surface of another metal *B* disappeared after a few seconds, being absorbed by the amorphous layer of the polished metal (see Plate VI).

Such diffraction patterns illustrate in other ways also the power of atoms to move a little even in the solid state. If a solution of cadmium iodide is poured on to a strip of celluloid and the water allowed to evaporate, a thin film of small crystals is formed. After all the water has evaporated, electron diffraction enables us to see that re-arrangement of the atoms is still taking place; two or three small crystals join to form one large one, even at the ordinary temperature of the laboratory.

The Beilby layer is not confined to metallic surfaces; a similar amorphous skin can be produced by polishing the crystal faces of some, but not all, minerals—for instance, zircon, tourmaline, moonstone, and the variety of felspar called orthoclase.

Moreover, electron diffraction enables us to find out the distances between the atoms on a surface, and in some cases the angles between three atoms in a surface. If we are considering a compound formed of two elements, *A* and *B*, thus : , we can learn the distances *AA*, and *AB*, and the angle *ABA*. This has enabled us during the last four years to check the molecular structure of very many important compounds. There are two or three other methods known for ascertaining the distances between the atoms in a compound, but they are difficult to explain, and it would add considerably to the length of this book if we were to discuss them properly and show in detail how all the results have been obtained. Nevertheless it may be of interest to set out some of the results, because they do show how chemical substances are built up, which is one of the purposes of this book.

By electron diffraction it has been found that the distance between the two atoms of bromine in the molecule of bromine is nearly 2·3 A. By the same method the atoms in the molecule of CO_2 are found to be in a straight line O–C–O and the distance between the two oxygen atoms is nearly 2·3 A. The molecule of phosphorus trichloride, PCl_3, is a pyramid the base of which is an equilateral triangle with a chlorine atom at each corner, the phosphorus atom occupying the apex; the distance between two chlorine atoms is nearly 3·2 A, and the distance between the phosphorus atom and a chlorine atom is nearly 2·0 A. Similarly it has been found that the molecule of carbonyl chloride, $COCl_2$, is shaped thus :  ; the distance CO is about 1·1 A, CCl about 1·8 A, and ClO is about 2·6 A. There are other methods of finding interatomic distances, *e.g.*, by *X*-ray examination of crystals and by band spectra. The results are in good agreement with those found by electron diffraction.

CHAPTER XVI

THE MYSTERY OF CATALYSIS

CATALYSIS is a word invented to describe a very common type of chemical action in which a third substance, the catalyst, helps two other substances to react. The catalyst seems almost to act as the master of ceremonies in an old-fashioned ball, introducing partners to each other, but taking no other part in the performance.

A very simple experiment that can easily be performed in any room illustrates the way in which a catalyst may act. If you try to set fire to a lump of sugar with a match, you will find that though you may soften and char the sugar, it is practically impossible to make it ignite. If, however, you touch a corner of the lump with a little cigarette ash—a very small speck will do—the sugar can easily be lighted at that corner, and will burn with a bluish flame. We are not asserting that catalysis is necessarily the explanation of this phenomenon; there may be some other explanation. But in any event it bears some superficial resemblance to catalysis, and although we do not know exactly what happens to the minute speck of cigarette ash that will work the trick, neither do we know exactly what happens in many undoubted instances of catalysis.

Sometimes very little suffices to start a chemical change; sometimes a great deal of effort is necessary. Iodide of nitrogen, NH_3NI_3, is a black powder that can be obtained by mixing together alcoholic solutions of iodine and ammonia. When it is dry it is very unstable, and if it is touched with a feather it explodes and emits a violet vapour. Some years ago this experiment used to divert school-boys from more serious labours. The safest way to carry out the experiment in our experience is to take the damp powder into a field and place it on a heap of stones, and when it is dry to throw stones at the heap; this introduces an element of skill and perhaps competition. There are many other explosive substances that undergo a rapid chemical change, the solid being converted wholly or partially into a large volume of gas, by heat, or a blow, or the explosion of a percussion cap.

A mixture of an inflammable gas with oxygen or air may be exploded by a very small spark, and many disasters have been so caused in coal-mines, where firedamp (methane), CH_4, oozes slowly into the air from the coal and forms an explosive mixture. In cordite factories, where there are not only large quantities of cordite but also inflammable vapours that may escape into the air, the utmost precaution must be taken to avoid a flame or a spark, and those who worked in such factories during the War will remember how special shoes without nails had to be worn, and how strict were the rules about matches and other lighting appliances. A mixture of chlorine gas and hydrogen remains unaltered in the dark; in a moderate light the gases slowly combine together to form hydrochloric acid; in bright sunlight the mixture may explode.

If a warm platinum wire is placed over the mouth of a bottle containing methylated spirit, the vapour of the alcohol in the spirit combines with the oxygen of the air at the surface of the platinum, and the wire will become red hot. So, too, if spongy platinum is placed over the mouth of a bottle from which hydrogen escapes into the air, the hydrogen will unite with the oxygen at the surface of the platinum, and this will become so hot that the hydrogen will catch fire and burn with a flame. A lamp was constructed on this principle by Dobereiner in 1823, and used for lighting purposes before the invention of lucifer matches.

A slight change in circumstances, or the mere presence of an additional substance, of which the platinum we have mentioned is an instance, may suffice to start a chemical action, and may also hasten a chemical action once this is started. If you heat potassium chlorate, $KClO_3$, you can drive off some of the oxygen, but the process works much quicker if some manganese dioxide is mixed with the potassium chlorate, and yet, curiously enough, the manganese dioxide is found intact at the end of the experiment. Sometimes very small quantities of an additional substance are sufficient to hasten an action very considerably. Hydrogen peroxide, H_2O_2, is a colourless liquid that has occasionally been used to alter the colour of the human hair; if it is mixed with hydriodic acid, HI, the acid breaks up and deposits iodine, and the rate of this action is more than doubled by the presence of molybdic acid in so dilute a solution as about one part in a million. The presence of a minute quantity of copper compounds greatly promotes the oxidation of sodium sulphite, Na_2SO_3, to form the sulphate, Na_2SO_4. Very many examples of this phenomenon could be given; enough to fill a long chapter.

In the year 1831 Peregrine Phillips, a vinegar-maker of Bristol, discovered that in the presence of platinum, sulphur dioxide, SO_2, would combine with oxygen to form sulphur trioxide, SO_3, the substance that combines with water to form sulphuric acid, H_2SO_4. No practical use was made of this discovery for many years, for it was found that the platinum soon became contaminated and the oxidation of the sulphur dioxide became slower and slower. Rudolph Messel between the years 1871 and 1875 closely investigated this problem, and found that the contamination of the platinum was usually caused by arsenic. Sulphur dioxide was commonly made by roasting pyrites, a sulphide of iron, which often contains copper sulphide, and a small quantity of arsenic sulphide. Consequently sulphur dioxide usually contained a small proportion of arsenic, and so did the ordinary commercial sulphuric acid. Messel found that if the sulphur dioxide was purified by passing it over an oxide of iron, which absorbs the arsenic, the platinum would remain clean for an indefinite period and its catalytic action remained unimpaired. In this way an important industrial method—the "contact" process of making sulphuric acid—was developed. The far older process of making sulphuric acid was also a catalytic process. In this the SO_2 was oxidized by mixing it with air containing oxides of nitrogen, which gave up a part of their oxygen to the SO_2, making SO_3, and then the oxides of nitrogen absorbed more oxygen again from the air. In this case the oxides of nitrogen acted as the catalyst.

The manufacture of synthetic ammonia is another catalytic process, based upon the researches of Haber and Le Rossignol in 1907 and the following three or four years. Nitrogen and hydrogen are passed at a pressure of about 100 atmospheres over a metallic catalyst, usually some form of iron, and they combine thus:

$$N + 3H = NH_3.$$

The production of ammonia is the first stage in the industrial use of the nitrogen in the air. The next stage is the production of nitric acid and the nitrates. Kuhlmann in 1830 found that if ammonia vapour was mixed with air and passed over platinum, it became oxidized to form nitric acid, HNO_3. During the Great War this method was developed on a huge scale in Germany, and since the War it has been similarly developed by Imperial Chemical Industries at Billingham in England and in other places in several foreign countries.

At Billingham many thousands of tons of ammonia compounds and of nitrates are manufactured every year. These are mainly used as fertilizers for enriching our arable land, pastures, and meadows, but some of the nitrates are used as explosives in coal-mining, gold-mining, and other industries.

Acetylene is an inflammable gas formerly much used for lighting purposes in out-of-the-way places, for it is very easily made by pouring water on to calcium carbide, a solid substance that is easily transported. Acetylene is a compound of carbon and hydrogen with the formula C_2H_2; if it is passed into water to which have been added sulphuric acid and sulphate of mercury, the latter acts as a catalyst, combining with hydrogen and oxygen, and then releasing these elements in a state that enables them to combine with the acetylene to form acetaldehyde in accordance with this equation:

$$C_2H_2 + H_2O = CH_3CHO.$$

Acetaldehyde is a chemical substance of some importance, for from it many other substances may be made, including acetic acid and acetone. Acetic acid is the acid contained in vinegar, and it is used in large quantities in the artificial silk industry. Acetone is a solvent used in industry. The manufacture of acetaldehyde in accordance with the above equation is carried on at a temperature above the boiling point of the acetaldehyde, which is removed as a vapour and then condensed to the liquid state. Solid manganese acetate is then added to the liquid and oxygen is passed through it; the oxygen unites with the acetaldehyde to form acetic acid, and the presence of the solid manganese acetate prevents the formation in any appreciable quantity of a violently explosive acid, peracetic acid, which would otherwise be formed. The manganese acetate appears to remain unaltered during the process, and in this respect it may be regarded as a catalyst. The equation representing the conversion of acetaldehyde into acetic acid is this simple one:

$$\underset{\text{acetaldehyde.}}{CH_3{\cdot}CHO} + O = \underset{\text{acetic acid.}}{CH_3{\cdot}COH}$$

This process was employed on a large scale in Canada and England during the Great War, when there was an exceptional demand for acetic acid.

The hydrogenation of coal so as to produce petrol is now an important industry carried on at Billingham. We have no petroleum wells in this country, and all the petrol and motor spirit we use here, except about four per cent., has hitherto been imported and has to be paid for by sending gold or goods abroad. The preparation of petrol from coal is by a catalytic process. The coal is powdered and mixed with oil in large cylinders made of special steel; hydrogen is pumped into the mixture at about 200 atmospheres pressure and at a temperature of about 450° C. Many catalysts have been tried, and the sulphides of molybdenum, tungsten, and some other metals were found to be quite successful. The hydrogen combines with the coal to form a mixture of what are called heavy oils, middle oils, and light oils. This mixture is distilled, and so separated into these three fractions; the heavy oils and middle oils are then treated with a further quantity of hydrogen at a suitable pressure and temperature, and are in this way converted into petrol. It is also possible to hydrogenate coal-tar so as to produce petrol, and this operation is carried on at Billingham. The output of petrol at Billingham is now about 400 tons a day—that is to say, about 4 per cent. of the country's requirement of motor spirit, and roughly equal to the whole supply of benzol and other motor spirit from all the gas-works and coal-distillation plants in this country.

The catalyst best fitted for a particular operation has usually been found out by a long series of careful experiments, but sometimes it has been discovered by accident.

In the manufacture of aniline dyes a substance called phthalic anhydride is used in very large quantities, and it became important to discover a cheap process for its manufacture. In 1896 a German chemist named Sapper was engaged in trying to make phthalic anhydride by heating naphthalene in sulphuric acid; he placed a thermometer in the vessel containing these substances and by a lucky accident the thermometer was broken and some of the mercury escaped into the mixture. The action which had previously been slow, became very rapid, and Sapper soon found out that mercury or sulphate of mercury was an admirable catalyst for this particular action.

Oxygen often acts as a catalyst, and as oxygen is present in the air, and air is present in so many chemical operations, its catalytic action long remained unnoticed. The actions proceeded quite normally, and the effect of the oxygen was not appreciated until attempts were made to conduct the operation *in vacuo* or to replace the air by some other gas, such as nitrogen. Even the glass of a flask or retort may act as a catalyst, and during recent years so many substances have been found to act as catalysts for some operation or another that it seems probable that almost every chemical action is much assisted by the presence of a catalyst. Perhaps no chemical action takes place unless a catalyst is present.

Water may also act as a catalyst. Dixon showed so long ago as 1880 that carbon monoxide does not combine with oxygen under the influence of the electric spark when the mixed gases are perfectly dry; when there is a trace of moisture the combination takes place with great rapidity. A similar result is observed when dry hydrogen and dry oxygen are mixed and an electric spark is made in the mixture; nothing happens. But if there is a trace of moisture a violent explosion takes place. Sodium has a great attraction for oxygen and it normally oxidizes very rapidly, but dry sodium may be melted in dry oxygen without any action taking place; and H. B. Baker found that perfectly dry ammonia gas and hydrochloric acid gas do not unite to form ammonium chloride, but the slightest trace of water vapour immediately promotes the combination. The absence of water does not entirely prevent the combination of carbon monoxide and oxygen; it makes it much more difficult. Bone has recently proved that perfectly dry carbon monoxide and oxygen can be exploded if a more powerful spark is used or if the gases are compressed.

We have been writing and thinking rather of the chemistry of mineral substances, but what we have just stated about catalysts is equally true of the chemical actions that take place in plants and animals. The production of starch by the potato, of sugar by the beet, of the green colour of the cabbage, and the purple colour by the violet are started and controlled by what are called "enzymes" which act as catalysts. In animals the whole process of digestion is started and controlled by enzymes or other agents which act as catalysts. The nerves in the human body act by means of such catalysts. Our muscular actions are accompanied by chemical changes in the muscles, and all the complicated changes in our normal life are controlled by minute quantities of things that act like catalysts. An enzyme is responsible for making the light emitted by the glow-worm, and for the luminous activity of the small organisms which sometimes in the seas around our coasts make the whole water phosphorescent when it is stirred by a boat or a shoal of herrings. The light of the firefly and the phosphorescence of decaying wood are also due to the action of an enzyme. In the chemistry of mineral substances we can usually isolate the catalyst, and manufacture it specially for use in the operation. So far as plants and animals are concerned very few of these enzymes or similar catalysts can be isolated and, so far, none can be made artificially by chemists.

CHAPTER XVII

METALS AND ALLOYS

Most people, if they could bring themselves to sit down and think, would find that they knew a good deal about metals and alloys. The ordinary house has a thermomometer containing mercury, otherwise known as quicksilver, innumerable articles of iron and steel, some copper (really bronze) coins, silver coins and silver ornaments, nickel-plated goods, some zinc or lead in the gutters, lead in the wireless accumulator, plenty of tin in the form of a thin film on iron plates, some gold in ornaments, plenty of articles made of brass (an alloy of copper and zinc), and so on. The average motor-car has some vanadium steel, or tungsten steel, platinum points to the sparking-plugs, nickel-plated parts, chromium-plated parts, and possibly manganese steel. We are familiar with magnesium ribbon in the days when we are thrilled by fireworks; we have aluminium vessels in our kitchens, cerium metal in our cigarette-lighters, and we are possibly acquainted with arsenic, antimony, or bismuth. We have, no doubt, read of cobalt, molybdenum, rhodium, palladium, iridium, thorium, and uranium; it will therefore cause us no surprise to find that out of the ninety-two elements that are supposed to exist, about seventy are metals.

Most of the metals are found in various ores: lead and copper as sulphides, iron as oxides, nickel as sulphide, zinc as sulphide, magnesium as carbonate, and so on. The metals are prepared from the ores by the process of smelting, which is often the simple process of roasting with coal or coke. The metals, with the exception of copper and gold, are greyish or whitish metals, with a silvery sort of appearance. They are solids, except quicksilver, at ordinary temperatures, but an alloy of sodium and potassium is also liquid at ordinary temperatures. Many of the metals can be drawn into wires or threads and beaten into thin sheets; they are tough rather than brittle.

Few of us are acquainted with metals in a pure state; cast iron contains a small percentage of carbon, and a very small percentage of this impurity confers very valuable properties on the iron, making it easier to melt, easier to work, harder, and tougher. Gold is too soft to use in a pure state; it is commonly alloyed with a little silver. The metals are crystalline in their structure, and sometimes, by heating the metal until it is liquid or soft and allowing it to cool slowly, quite large crystals can be obtained. Rapid cooling usually produces very small crystals, often of microscopic size. The presence of impurities in the metal usually results in the formation of smaller crystals.

Pigs of pure lead often show crystals, so do castings of tin, bismuth, antimony, and tellurium. Crystals of pure iron can sometimes be obtained. When a molten metal cools, the crystals begin to form in a great many places, and they grow until they meet each other in all directions: they are consequently usually crowded together and distorted.

As a general rule, the purer the metal the higher is its melting point, and the larger are its crystals, so that the purest metals are the most difficult to cast or to work in a forge, and the finished metal is usually more brittle or softer than is desired. The metals most used industrially are therefore usually not quite pure.

Pure iron is difficult to cast, and the presence of a small quantity of carbon makes it a much better metal. Iron unites with carbon to form a compound, Fe_3C, called cementite. This compound contains $\frac{1}{15}$ of its weight of carbon, so that iron containing 1 per cent. of combined carbon will contain 15 per cent. of cementite. Iron containing more than about 0·3 per cent. of carbon is called steel, and the properties of the steel depend a good deal on the proportion of carbon.

Steel containing about ½ per cent. of carbon is used for rails and hard wire; that containing about 1 per cent. is used for cold chisels, miners' drills, and punches. Steels containing about 1½ per cent. of carbon are used for razors, surgical instruments, and various small tools.

If there is about 6·7 per cent. of carbon in steel, the whole of this steel or alloy will be cementite, and any proportion of carbon beyond this, if added to the molten metal, will separate out as graphite. The ordinary steels containing, say, ½ per cent. of carbon will be a mixture of 7½ per cent. of cementite and 92½ per cent. of iron, and these two substances may be in larger or smaller crystals, depending mainly on the rate of cooling.

Just as there are two varieties of carbon and half a dozen varieties of sulphur, differing from each other in their molecular arrangement, so there are three or four varieties of iron, the two most important being called α-iron and γ-iron. Of these α-iron is converted into γ-iron at a temperature of about 690° C. On cooling much of the γ-iron is reconverted into α-iron, but this process may take a long time, and if the steel is cooled quickly a good deal of the γ-iron remains unconverted. An ordinary steel may therefore easily contain a mixture of cementite, and γ-iron, and α-iron, and perhaps a little graphite. The relative proportions of these, the rate of cooling, and the methods of annealing, tempering, and working, all affect the properties of the steel.

It is therefore not surprising that there is an immense variety of steels, each of which is specially suitable for some special purpose. Most steels are cooled quickly by quenching them in water or oil; this makes them harder and more brittle. To make them suitable for most purposes they are then reheated and allowed to cool slowly. This is the operation called " tempering "; surgical instruments are heated to about 225° C., penknives to about 245° C., cold chisels and hatchets to about 255° C., table knives to about 275° C., and saws to about 320° C. At each of these temperatures the steel assumes a particular colour, due to a thin film of oxide formed upon the surface, and the experienced workman relies upon this colour to tell him when the correct temperature is reached.

Carbon is not an impurity in steel, but a necessary ingredient, that determines the character of the steel. Other substances that alter the character of the steel very much are silicon, sulphur, and phosphorus. Of these sulphur and phosphorus are on the whole objectionable elements, but silicon may impart quite useful properties.

We are by no means at the end of the varieties of steel and the various complications that affect its nature and properties. Manganese is sometimes added, and a very valuable alloy called manganese steel, containing from 10 to 15 per cent. of manganese, was discovered by R. A. Hadfield, now Sir Robert Hadfield, in 1882. It has been used for rails, helmets, and other purposes. A rustless chromium-steel alloy was discovered by Brearley in 1912, and there are other rustless steel alloys containing nickel and chromium. In addition to these, there are valuable chromium–vanadium steels used for shafts and gears in motor-cars, and tungsten steels used for shells and for valves in motor-cars and other parts which are liable to become hot. It is therefore difficult to lay down any general rules about the properties of iron or steel or to explain the effect of any one special method of treatment.

Copper is obtained from various ores, and is then dissolved in an acid and electrolytically deposited in a very pure state. The pure metal is an exceptionally good conductor of electricity, and is used for electric cables; quite small amounts of an impurity greatly reduce its conductivity. But for other purposes an alloy of copper is generally preferred. An alloy of 95 per cent. of copper and 5 per cent. of manganese is known as manganese bronze; the nickel coinage of the United States contains 75 per cent. of copper and 25 per cent. of nickel; the bronze commonly used for coinage in Great Britain contains 95 per cent. of copper, 4 per cent. of tin, and 1 per cent. of zinc. Bell metal contains 78 per cent. of copper and 22 per cent. of tin. The yellow brass contains about 67 per cent. of copper and about 33 per cent. of zinc. The alloy known as German silver contains about 50 per cent. of copper, about 30 per cent. of zinc, and about 20 per cent. of nickel. All these and a score more of copper alloys have special properties of colour, hardness, and so on, and they are used for some special purpose. Copper was one of the first metals known to mankind, and the element itself is found in small quantities in some places. Bronze, too, was known in Asia and Europe in prehistoric times.

Nickel is a metal that is used in large quantities for nickel plating and for making alloys with iron, copper, and other metals. A mixed ore of nickel and copper is found in great quantity in Canada, and from the mines there a matte containing about 41 per cent. of nickel, 41 per cent. of copper, and about 17 per cent. of sulphur is exported to Great Britain, where it is treated by the Mond process, discovered by Dr. Ludwig Mond and Dr. Carl Langer in 1886. The matte is roasted and treated with sulphuric acid to remove the copper. The nickel oxide left is treated with water-gas, a mixture of carbon monoxide and hydrogen, which reduces the nickel oxide to the metallic state. To free it from impurities it is heated to about 80° C. and carbon monoxide is led over it; the nickel and carbon monoxide unite to form a gaseous compound, nickel carbonyl, $Ni(CO)_4$, which is passed over pellets of nickel at a temperature of 180° C.; at this temperature the $Ni(CO)_4$ breaks up, depositing the nickel in a pure state and setting free carbon monoxide, which is used again in the process.

For some purposes—for instance, aeroplane manufacture—it is important to make use of the lightest possible metals that are sufficiently strong. Among these the alloys of aluminium and magnesium have been largely used. Duralumin is an alloy containing 94·4 per cent. of aluminium, 0·95 per cent. of magnesium, 4·5 per cent. of copper, and 0·76 per cent. of manganese; it has a specific gravity of about 2·96—that is, it is less than half as heavy as iron or copper. There are alloys known as lynite containing about 92 per cent. of aluminium, about 7 per cent. of copper, and 1 per cent. of other metals; different varieties of lynite have been used for aeroplane engines. The magnalium alloys are even lighter than duralumin, the magnalium alloy containing 90 per cent. of aluminium and 10 per cent. of magnesium has a specific gravity of 2·5 and still lighter magnalium alloys have been made. There are other alloys known as dowmetal and electron containing about 90 per cent. of magnesium, and a small percentage of aluminium, copper, and zinc. Some of the electron alloys are now being used in large quantities in connexion with aeroplane equipment.

We are accustomed to regard solids in general, and perhaps metals in particular, as rigid bodies, remaining unchanged for ever, but the atoms in many solids are not, in fact, stationary, but are capable of movement to a small extent. This is easy to demonstrate in the case of metals. If a clean lead cylinder is placed upon a clean gold plate and left there, a little of the gold will penetrate into the lead, and may even in course of time find its way to the very top of the cylinder. It is hard for us to believe that the solid rigid metals are mainly consisting of empty space through which atoms are creeping and crawling and arranging themselves in one pattern at one temperature and in another pattern at a higher temperature, but this seems to be the case. No doubt as the temperature rises the speed of the atoms increases and, of course, there is a far higher speed in liquid metals than in solid ones.

Sodium and potassium are silvery-looking metals that oxidize very rapidly on exposure to air or water; they must therefore be kept in such a liquid as naphtha, which, like the paraffins, contains no oxygen.

If a number of lumps of solid sodium and solid potassium are placed in a bottle containing naphtha, there is enough movement in the atoms to enable the sodium atoms to penetrate the lumps of potassium, and vice versa. Gradually an alloy of potassium and sodium is formed, and this is liquid at ordinary temperatures and looks something like mercury. Both sodium and potassium will dissolve in this alloy, and soon the whole of the sodium and potassium will be united to form a silvery liquid. Solid sodium and solid potassium consist of atoms of the respective elements not packed together as closely as is theoretically possible, but still packed together to occupy a volume only about 10 per cent. greater than the closest theoretical one. Sodium and potassium are constructed on the body-centred cubic system in which the atoms are arranged at the corners and the centre of a set of cubes. We suppose that as the distance between the adjoining atoms in potassium is greater than the distance between the adjoining atoms in sodium, in the alloy of the two there will not be the same possibility of close packing as there is in either metal separately, and so there will be a greater possibility of movement of the individual atoms; that means that the alloy will have a lower melting point and the liquid state of the alloy is explained. Potassium melts at 62° C., sodium at 97° C.; the alloy of the two is liquid at ordinary temperatures—say, 15° C.—for a wide range of proportions of the two.

This lowering of the melting point is a very common feature of the alloys. Tin melts at 232° C., and lead at 327° C., but a mixture or alloy of the two—solder—melts at a temperature between 198° C. and 205° C., depending on the proportion of the two. The addition of bismuth and cadmium to solder lowers its melting point still further. Bismuth melts at 268° C., and cadmium at 321° C., but an alloy of 15 per cent. of tin, 31 per cent. of lead, 38 per cent. of bismuth, and 16 per cent. of cadmium melts at 71° C. If a spoon is made of such an alloy, it melts if used to stir a cup of hot tea; this particular alloy is known as Wood's alloy or Wood's metal.

Most metals when they are exposed to the air, especially moist air, corrode and tarnish—that is, generally, they are oxidized by the air. Gold and platinum do not oxidize. Some metals are easily affected by the carbon dioxide in the air, and a film of oxide mixed with carbonate may be formed on the surface of the metal. If the air is so moist as to deposit minute drops of water on the metal, the corrosion is usually much greater. Silver articles quickly tarnish in foggy weather when the air is very moist, but if the articles are wrapped up in a handkerchief they tarnish much less, because the minute drops of water are deposited on the handkerchief rather than on the metal. In some cases the layer of oxide or carbonate formed on the metal when it corrodes is soft and flaky; in other cases it is hard and resistant. Zinc forms a soft film, lead a hard one; iron in moist air forms a soft film at ordinary temperatures, but a hard film if the iron is heated. Aluminium forms a hard film. The hard films are a great protection against further corrosion, and even when they are so thin as to be invisible, they are effective in preventing rust or tarnish. The presence of small quantities of impurities in the metal affects very much the nature of the film formed on exposure to the air and the consequent degree of corrosion; but corrosion is a most complicated matter, and is not easy to explain in general terms, because it depends on the chemical composition of the metal, the chemical composition of the air or liquid to which it is exposed, the degree of moisture, the temperature, and at least half-a-dozen other circumstances, all of which have to be considered, before the problem can be really understood.

When iron or steel rusts in the open air, most of the oxide of iron formed gradually finds its way into the soil or is washed by rain into a drain or a stream, and finally is dissolved and runs into the sea. Whatever its ultimate fate, it becomes very finely divided, and mixed with a large quantity of earth or water, so that it cannot be profitably recovered. The amount of iron and steel lost in this way is enormous. Some years ago Sir Robert Hadfield estimated that the corrosion of iron and steel throughout the world in each year involves a loss of £500,000,000. A portion of this loss is inevitable, but some could be avoided by the use of more paint and other protective surfaces.

CHAPTER XVIII

COMBUSTION AND EXPLOSION

THE burning of a coal fire or a heap of dead leaves, the lighting of a gas jet, the rusting of an iron railing, the respiration of mice and men, the phosphorescence of a glow-worm, or fire-fly, the working of the internal-combustion engine in our motor-car, and the bursting of a shell filled with a high explosive, are all examples of oxidation, an operation that is familiar to us all. Let us consider some of the simplest of these and postpone the respiration of animals and the glowing of the worm and fly, which are rather more difficult to explain.

We strike a match the head of which contains two kinds of substances: one that is ready to combine with oxygen, the other containing oxygen. These two substances remain in contact with each other quite quietly, but the friction of the match on the box or some other surface raises the temperature of the head of the match to such a point as to start a chemical action between the substances in the head. A rise in temperature commonly increases chemical activity; for this reason plants grow faster in the summer than in the winter. The oxidation of the match-head is sufficient to raise the temperature of the wood of the match to the point when it begins to give off a gas or vapour; this gas takes fire and produces a flame. The mere fact that there is a flame is evidence of the existence of a burning gas, and wood, if heated, gives off a gas of the same general nature as the gas obtained by heating coal.

Having now obtained a light in a way that is far more convenient than the tinder-box in use a hundred years ago, we apply the match to the paper at the bottom of the grate, upon which sticks and coal have been suitably, or unsuitably, placed. Paper has nearly the same chemical composition as wood and if you heat it, it evolves a gas. If you roll a strip of paper spirally so as to make a spill and close the large end and apply a light to the small end, you will find that, as the paper gradually burns, a smoky gas comes off at the small end and this gas will burn with a bright whitish flame. So, too, the paper in the grate, *so soon as it is lighted, gives off a gas the flames of which* heat the wood until this also gives off a gas. This gas in contact with the air burns; that is the hydrogen, the CH_4, and other constituents of the gas unite with the oxygen of the air to form carbon dioxide and water.

The heat from the burning wood causes an evolution of gas from the coal, and this takes fire too; you can sometimes see little " blowers " of gas escaping from the hot coal when there is no flame near enough to set them alight. After the gas has been driven out of the coal there is left a sort of coke, consisting mainly of carbon. This will become hot, and slowly oxidizes away, but it does not always give a flame. All these operations need a plentiful supply of oxygen, a fact that is occasionally forgotten. When you have hot carbon in a plentiful supply of air it seems that a solid oxide or mixture of oxides of carbon can be produced. As the temperature rises this solid oxide breaks up, forming a mixture of carbon monoxide and carbon dioxide; the proportion of these two depends mainly on the supply of air. If there is plenty of air there will be only a small proportion of carbon monoxide formed, and this will be promptly oxidised into carbon dioxide.

The fire may be so arranged that there is a layer of hot coke above the part where the most active combustion is taking place. This coke may act upon the carbon dioxide that reaches it, forming carbon monoxide, thus:

$$C + CO_2 = 2CO.$$

The carbon monoxide thus formed, when it finds its way through the layer of coke into a place where there is air, will burn thus:

$$CO + O = CO_2.$$

When carbon monoxide burns to form carbon dioxide it makes a bluish flame, often seen in an ordinary coal fire. Finally all the gas will have been driven off the coal and burned, all the coke will have been burned, and there will be nothing left except a little ash consisting of mineral matter contained in the coal.

In the burning of leaves, sticks, and weeds in the garden the main principles are the same, but as the weeds are usually wet, the operation is more difficult, and requires long experience and close attention. So much steam is given off from the weeds, and they are generally piled so thick on each other, that the combustion is slower and not so complete. It is the incomplete products of combustion that provide the delightful aroma of a good garden fire. In such a fire at last everything that can be burned has been burned, the carbon to carbon dioxide, the hydrogen to water, the nitrogen in the plants to oxides of nitrogen, and so on. The ash contains a little oxide of potassium, oxide of calcium, oxide of iron, oxide of magnesium, oxide of silicon, and other substances. This ash contains mineral materials carefully collected by plants from the soil; plants need much mineral substances and the ash from the bonfire should be restored to the soil so as to preserve its fertility.

The burning of coal-gas is not a very complicated matter; when coal is heated in a retort it gives off a gas which is a mixture of hydrogen, methane (CH_4), carbon monoxide, and a little nitrogen and oxygen. About half the volume of the gas is hydrogen, rather more than a quarter is methane; in addition to the methane there are small quantities of other compounds of carbon and hydrogen. Coal gas was formerly used to give a bright flame, and the brightness was entirely due to the presence of these small quantities of other compounds of carbon and hydrogen. At the present time is not desirable for the gas to give a bright flame; it is used to heat an incandescent mantle; this mantle gives the light, and the gas is merely used for heating. The small quantities of other compounds, if they were left in the gas, would not contribute much to its heating power and would tend to spoil the mantle. These other compounds are now carefully removed from the gas; one of them, benzene or benzol, is a valuable fuel. In former days gas was sold by the cubic foot, but since it became used solely for heating purposes, including heating a mantle, it was valued at so much a heat unit, the therm.

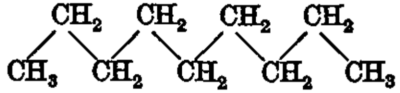
Hydrogen, methane, and carbon monoxide all burn with a colourless flame; they have all good heating properties, and as a mixture of hydrogen and carbon monoxide is very cheaply made, it is now very commonly added to coal-gas and mixed with it. This mixture of hydrogen and carbon monoxide is called water-gas and is made by passing steam through red-hot coke. The coke, which is carbon, combines with the oxygen in the steam to make carbon monoxide, leaving the hydrogen uncombined. In the combustion of gas the cold gas is led through a pipe into cold air, and when once the oxidation is started by a match the chemical action between the gas and the oxygen of the air provides all the heat. This chemical action only takes place where the gas and the air meet, and that is just the outside of the flame; the flame is hollow and the inside of it is cold gas.

The rusting of iron exposed to the damp air is a sort of slow and mild combustion. The water vapour in the air and the carbon dioxide in the air have their effect on the iron, in addition to that of the oxygen, and so the rust may contain oxide of iron, and hydrate, and carbonate, but in the course of years the iron will gradually be converted mainly into an oxide. No doubt a little rise of temperature takes place when the iron and oxygen unite together, but it is too small to be noticed.

A stick of phosphorus exposed to the air gives a faint glow caused by the slow union of the phosphorus and oxygen. So, too, the phosphorescence of the glow-worm and the fire-fly is due to a slow oxidation of some of the parts of these insects. It might be thought that if this is the true explanation, as the oxidation is always going on the glow-worm should always be glowing, which we know is not the case. It is true that the oxidation is always going on, but it is only an exceptional kind of oxidation that causes a glow, and this kind is not continuous.

In birds and mammals the muscles and most of the other tissues of the body contain compounds of carbon, hydrogen, and oxygen and of carbon, hydrogen, oxygen, and nitrogen that are capable of being oxidized so as to form, amongst other products, carbon dioxide and water. The oxygen is being continually brought to the tissues of the body by the blood, and the blood carries away the carbon dioxide and water formed. There is consequently a continuous process of combustion going on, the cause of the warmth of the bodies of such animals. The rate of combustion in the body is automatically controlled and is quite independent of the amount of fuel present in the body. We need not discuss this now, as we deal with it later; we only mention it now as one of the many varieties of combustion.

Let us consider the combustion of petrol in the internal-combustion engine of an ordinary motor-car. Petrol is a mixture of hydrocarbons, compounds of hydrogen, and carbon; some of these consist of chains such as this:



Other hydrocarbons contained in petrol are derivatives of benzene, and they have as part of their structure a ring of six carbon atoms; these are called aromatic hydrocarbons, because some of the compounds containing a six-carbon ring have a pleasant smell.

In the cylinders of a motor-car a mixture of petrol vapour and air is compressed; when a gas or vapour is compressed it becomes hotter, and the hotter it is the greater pressure it exerts on the walls of the cylinder. At the right time an electric spark explodes the compressed mixture; oxidation of the hydrocarbons takes place rapidly, and the temperature again rises. The effect of this oxidation and rise of temperature is to drive the piston steadily in the direction intended. When the engine is running properly the explosion in the cylinder is rapid, but not excessively rapid. On the other hand, if the engine is driven to the limit of its power, the compression of the petrol vapour and air in the cylinder may become so great and the temperature so high that the explosion takes place without waiting for the electric spark. In this case the explosion is excessively rapid, and instead of driving the piston steadily along the cylinder, it "knocks" it. This knocking is brought about by the explosion of the long-chain hydrocarbons, not the aromatic ones. The aromatic hydrocarbons tend to prevent "knocking," and they are often added to the petrol for this very purpose.

There are other substances that have the same effect, and the best of these is lead tetraethyl, $Pb(C_2H_5)_4$; the addition of a small proportion of this prevents knocking and increases the power of the engine to a notable extent; in almost all the speed records of modern times petrol containing lead tetraethyl has been employed. This quality of lead tetraethyl was discovered by an American chemist T. Midgley in the year 1922.

The Diesel engine is specially constructed so that no electric spark is necessary. The mixed gases in the cylinder are compressed until they explode and the engine is designed accordingly. A heavier and cheaper oil can be used in the Diesel engine, and the number of these engines in use is increasing rapidly.

In an ordinary flame, such as is obtained when a stream of vapour passes into the air and is lighted, the vapour burns at a steady rate. But if a vapour—or gas, for these are the same things—is allowed to mix with air until there is a large volume containing enough combustible vapour and enough oxygen, then we get a mixture that only needs a spark or a tiny flame to set the whole alight. Near the spark a few molecules of the vapour and oxygen combine together, and the combination provides enough heat to make all the adjoining molecules of vapour oxidize; more heat is made, and so, after a very brief interval, the whole mixture explodes. As the effect of the explosion is to raise the gases to a high temperature, they expand rapidly, and can easily cause a disaster. In a confined space the force of the explosion is concentrated and the effects are more dangerous. The time taken by the explosion varies very much; if two volumes of hydrogen and five volumes of air (one volume of oxygen and four volumes of nitrogen) are exploded together in a confined space the maximum pressure will be reached in about one hundredth of a second. But carbon monoxide exploded with the proper amount of oxygen and nitrogen takes forty times as long to reach the maximum pressure. The nitrogen plays a small part in the explosion for various oxides of nitrogen are formed in its later stage. The effect of this is rather unexpected; the presence of nitrogen usually delays the explosion a little; if argon, which is inert, is used instead of nitrogen the explosion is more rapid.

If an explosive mixture is contained in a long glass tube and an electric spark is made at one end, the explosion and the flame accompanying it will travel rapidly along the tube. By means of a special camera, the Fraser high-speed camera, it is possible to photograph the flame as it travels, using a succession of exposures each of one millionth of a second.

The explosion of solid substances differs from the explosion of gases in degree rather than in nature. All solid explosives contain something capable of existing as a gas, and they have this characteristic, that when the atoms of the substance are rearranged so as to make the gas a rise in temperature takes place. The rearrangement is usually started by heat, a blow, or an adjacent explosion.

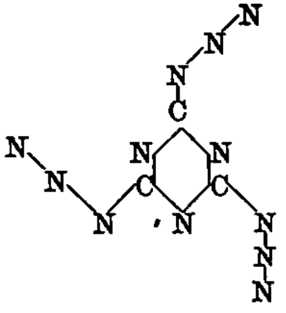
The compounds of nitric acid form an important group of explosive substances. Nitric acid is HNO_3, and obviously it contains a large proportion of oxygen In fact nitric acid contains:

Hydrogen . . .	1	part by weight.
Nitrogen . . .	14	parts „
Oxygen . . .	48	„ „
	—	
	63	

so that the oxygen contributes more than three-quarters of the weight of the nitric acid. Nitric acid is not itself explosive, but many of its compounds are. Ammonium nitrate, NH_4NO_3, can be exploded and it produces water and oxides of nitrogen in vapour form at a high temperature. Glycerine is a compound of carbon, hydrogen, and oxygen, and nitroglycerine is a compound of glycerine and nitric acid. In nitroglycerine there is enough oxygen to oxidize all the carbon, hydrogen, and nitrogen forming gases at a high temperature. Trinitrotoluene, well known during the Great War as T.N.T., has the formula $C_6H_2(CH_3)(NO_2)_3$; and it has enough oxygen in it to oxidize the carbon to carbon dioxide, the hydrogen to steam, and the nitrogen to oxides of nitrogen, all at a high temperature. Its explosive properties are thus easily explained.

Gunpowder is a mixture of charcoal (carbon), sulphur, and saltpetre (potassium nitrate, KNO_3); it contains enough oxygen to oxidize the carbon to carbon dioxide, and the sulphur to sulphur dioxide, and to form, in addition, some oxides of nitrogen, and oxide of potassium; all these except the last are gases, and, especially when hot, they occupy a far greater volume than the gunpowder. It would be possible to make a long list of the explosive substances prepared from nitric acid, but it is not essential to our purpose.

There are other compounds of nitrogen that are explosive not because they contain so much oxygen, but because they contain so much nitrogen. A rather interesting one, discovered only a few years ago, is the solid cyanuric triazide, $C_3N_3(N_3)_3$, the structure of which is shown by this diagram:



This readily breaks up, producing cyanogen, C_2N_2, and nitrogen, both of which are gases. It happens that this cyanuric triazide has been carefully investigated by *X*-rays, and the exact positions of all the atoms in it are known. Perhaps we are wandering a little from our subject; still one thing does lead on to another unless you keep yourself in check.

CHAPTER XIX

LIVING THINGS

We have now said what we intended to say about the nature of matter in general: the way in which it is built up of nuclei and electrons, the activities of the electrons in causing chemical attraction, and the curious intricacies of chemical change; we come to a consideration of life, and we must limit ourselves to a discussion of the same sort of problems as we have dealt with in the first part of this book, but in relation to living things, and not inanimate substances.

There are obviously great differences between living organisms and inanimate objects. What are the essential differences? This is no easy question to answer. We regard as typical of living creatures, plants or animals, the power of reproducing their species, and the fact that the dead organisms differ essentially from the living ones. The moment a living organism dies it begins to putrefy or decompose; the complicated substances of which it is composed undergo a variety of chemical changes from which no recovery is possible. While it was alive it maintained a sort of equilibrium, remaining one day very much like what it was the previous day, absorbing something from the air, something from its food or the soil, making use of some constituent from these, rejecting what was not needed, and so maintaining its status. After its death the control ceases and decomposition begins.

Some of the terms we are using are necessarily rather vague. In the case of plants what are we to consider as death? A leaf falls from the tree; exactly when does it die? We do not know. We cut a twig from a tree and stick it in the earth; it may take root, put forth leaves, and become a new tree; or is it just a separate part of the old tree? The apple falls from the branch and is stored in a cupboard; it does not die at once; perhaps it is nearly ripe, and for a period of a few weeks or a few months it will retain all the characteristics of the living fruit when still attached to the parent tree. It goes on living, absorbing something from the air, giving out vapours from its substance, slowly converting its starch into sugar, steadily ripening. The pomegranate, plucked green, ripens far over the sea, as the poet says. The seed in the core of the apple undergoes its own set of changes, and will remain dormant but living for a very long period, until either it finds its way into a suitable soil or until it withers and dies.

The power of movement is not a conclusive test of life; the dormant seed that we know so well remains in the nurseryman's drawer or bin for months, and has no more power of movement there than the label on the packet. And yet the chemist can make a sticky sort of oily liquid which, if placed in water, puts forth a little lump or excrescence, withdraws it again, and it almost resembles in this power some of the very primitive living microscopic creatures, such as the amœba.

On the other hand, the crystal of alum or copper sulphate grows in its proper environment, and if a small piece is detached from it, the small piece will itself grow into a new crystal, and the scar left on the original crystal when the small piece was detached heals, and all traces of it disappear.

There are some features which very obviously distinguish animal and vegetable living substances from mineral substances; one is their extraordinary complexity; another is their ingenious structure; another is the automatic control of the chemical operations which are always taking place in living organisms.

Earlier in this book are some appalling diagrams and formulæ which the prudent reader has just glanced at and forgotten. Such a substance as granite, consisting of a mixture of three or four silicates of four or five different metals, seems rather more difficult to understand than such a simple molecule as H_2O or HCl. But the silicates themselves are simple when compared with the common substances of plants and animals. The smallest living organisms—bacteria, yeasts, and microscopic animals—have an organized structure built up of substances ten or a hundred or a thousand times as complicated as the simple molecules we have referred to. We cannot in general give the formulæ of these substances; we know a little about their nature and are getting to know more, but their formulæ cannot be written; only the simpler units of which they are built are known, and the way in which these simple units are combined is very imperfectly understood.

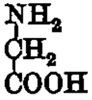
The simplest living organisms consist of a single cell with a cell-wall, in which is a watery fluid containing what is called protoplasm, a semi-solid, slimy sort of substance; in this mass of protoplasm is a more highly developed spot called a nucleus. The pansy and the apple in our garden consist of millions of cells interspersed with small pipes and vessels in which juices can travel, and bound together and stiffened by fibres of cellulose or woody tissue.

The cellular nature of plants and animals is one great characteristic that distinguishes these from mineral substances. The cell-wall is not impervious to all matter. Protoplasm cannot find its way through the empty spaces of the cell-wall; the substances of which it is composed have molecules far too large to enable this to take place. But many of the small molecules can find their way through the walls of the cells and vessels of plants and animals, and this is of the utmost importance to their life. If we make a dish or cylinder of parchment and place in it a mixture of water, alcohol, salt, starch, and gum, and then place the dish or cylinder in a tank containing water, we shall find the water in the tank will gradually contain more and more alcohol and salt, because these gradually find their way through the parchment, but the starch and gum will remain behind.

The cellular nature of living things is partly responsible for the slow way in which their chemical operations are conducted. If we take a flask nearly full of lime-water and add to it a solution of a carbonate, we shall find that the whole flask is instantly filled with a white precipitate of calcium carbonate. But when we eat a potato, the starch in the potato must first be broken up into simpler substances which can penetrate the wall of the alimentary canal and find their way slowly and gradually to their destination. They will then either be oxidized or will reunite to form a substance like a simple form of starch, and these operations will take perhaps a few hours. Not only will the operation of the transformation of the starch be slow because of the cellular nature of our body, it will also be slow because there are ten or twenty or more automatic controls which direct the nature of the various operations and the speed at which they are to work.

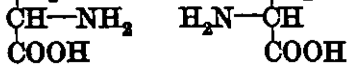
The plants and animals contain a very large proportion—often 80 per cent. or more—of water; the residue largely consists of three great classes of substances, proteins, carbohydrates, and fats. We must explain these terms before we can describe their functions in living things, and we will begin with proteins. The protoplasm which is contained in so many animal and vegetable cells consists principally of proteins; much of the cell walls of animals consists of proteins; the muscles of animals are mainly proteins, the walls of our blood-vessels are mainly proteins; our sinews, hair, and nails are mainly proteins. Dry yeast contains about half its weight of these substances; the soft parts of eggs are mostly proteins, and almost all fruits and seeds contain them. Many of the foods we eat contain proteins, and without these ingredients of our diet we cannot continue to live.

When we try to find out their nature and structure we are faced with the difficulty that we cannot analyse the proteins without breaking them up and destroying them. It is true that we can recognize some of the parts when we break them up, but is not this rather like recognizing a few columns or windows in the ruins of a building? We can only guess at the structure of the proteins, but we do know a good deal about the groups of which they are composed. To begin with, they are constructed of what the chemist calls amino-acids, amino because they contain the group NH_2. All the amino-acids that form parts of proteins contain such a grouping as this:  $-CH<^{NH_2}_{COOH}$, and very many of the amino-acids have been isolated and carefully studied. Among the units that help to build up the proteins are the following substances:

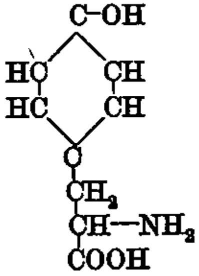


glycine.

alanine.

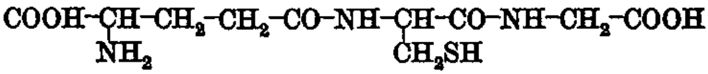


cystine.



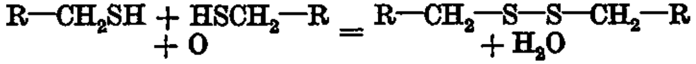
tyrosine.

Cystine, as we see from the formula, contains two sulphur atoms joined together, and there are other compounds in which such a grouping appears. There is a substance called glutathione, of quite common occurrence in the higher animals, first isolated by Gowland Hopkins in 1921. We mention it because it illustrates not only the structure of a part of a protein, but also the way in which a protein or a part of a protein may act as a catalyst or carrier in effecting oxidation. Oxidation in the animal kingdom is an essential part of digestion and respiration; it keeps up the temperature of the body and helps to supply the body with energy. An example of the various processes of oxidation is therefore quite appropriate to our subject. Glutathione has this constitution:



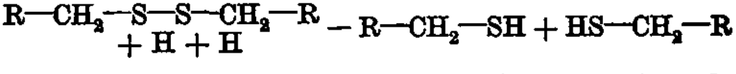
$$COOH\text{—}\underset{NH_2}{CH}\text{—}CH_2\text{—}CH_2\text{—}CO\text{—}NH\text{—}\underset{CH_2SH}{CH}\text{—}CO\text{—}NH\text{—}CH_2\text{—}COOH$$

To save space we will denote everything in the glutathione except the CH_2SH group by the letter R. Two molecules of glutathione readily remove an oxygen atom in their vicinity thus:



$$\underset{+\,O}{R\text{—}CH_2SH + HSCH_2\text{—}R} = \underset{+\,H_2O}{R\text{—}CH_2\text{—}S\text{—}S\text{—}CH_2\text{—}R}$$

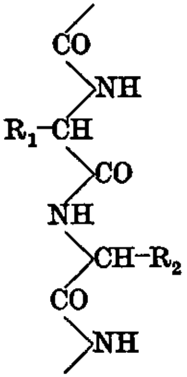
The compound $R\text{—}CH_2\text{—}S\text{—}S\text{—}CH_2\text{—}R$ readily removes two hydrogen atoms in its vicinity, thus:



$$\underset{+\,H\,+\,H}{R\text{—}CH_2\text{—}S\text{—}S\text{—}CH_2\text{—}R} = R\text{—}CH_2\text{—}SH + HS\text{—}CH_2\text{—}R$$

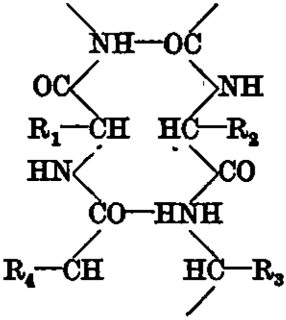
and in this way two molecules of glutathione are re-formed; so the glutathione acts as a catalyst or carrier in the removal of oxygen from some substance in the tissue or the removal of hydrogen from some other substance in the tissue; this appears to be its function in the animal kingdom.

When such substances as the amino-acids combine to form proteins or parts of proteins, they do this by forming long chains of groups of CO, NH, and CH, and the CH group is attached to R, where R denotes the residue of the amino-acid—that is, everything, except the COOH and the NH groups. The result is shown by such a diagram as this:

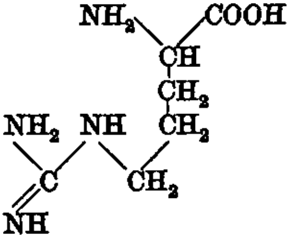


in which R_1 denotes a residue of one amino-acid and R_2 denotes a residue of some other amino-acid. A protein consists of an aggregation of many amino-acids, perhaps fifteen or twenty different amino-acids; thus the protein, gelatine, from which we make jellies, is a compound of glycine, alanine, leucine, proline, glutamic acid, arginine, lysine, and at least ten other amino-acids. Because of their industrial importance a good deal of attention has been paid to the proteins in animal fibres, and more is known about them than some of the other proteins. Nails, horns, bristles, and wool are mainly composed of different varieties of the protein called keratin. Sheep's wool and human hair have been investigated by *X*-rays, and although we do not know all the details of the structure of the keratin in wool or human hair, we have been able to learn the width of the chains of the keratin and the length of the groups in it, and something of the way in which one chain is connected with the adjoining chains.

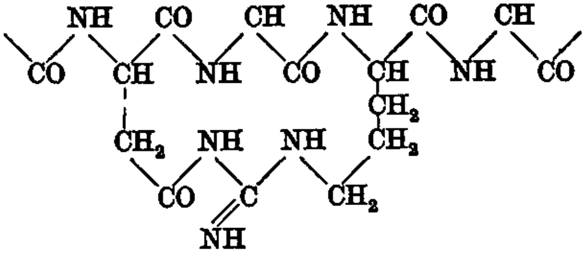
In keratin it seems that two adjoining chains are combined together in this manner, and in addition to the linkages between the opposite groups of HN and CO, there are also linkages to adjacent chains by means of the amino-acids residues R_1, R_2, R_3, and R_4 in the diagram.



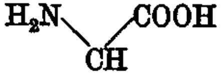
In the case of keratin many of these residues seem to be arginine residues. Argenine is an amino-acid of this structure :



and where it forms part of a keratin we get such an arrangement as follows :

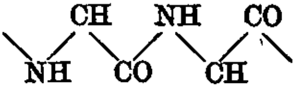


All this is, of course, very complicated, but it is no use shirking the problem because it is complicated; cell chemistry is not so simple as test-tube chemistry, and it is no good pretending that it is. But to many of us it is more interesting; and although it is complicated, it is not necessary to commit to memory all the complications. It is sufficient for our purposes to remember just the essential end part of the amino-acid, the

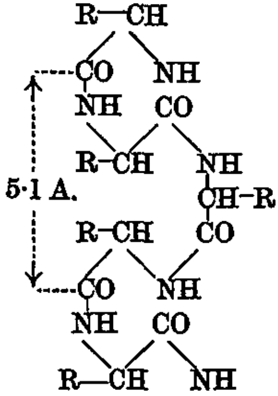


$\mathrm{H_2N{-}CH{-}COOH}$

and the chain made up of these units:



The human hair, like sheep's wool, is elastic, and can be stretched without breaking, and if it is not stretched too much it will return to its original length. By *X*-ray measurements it has been found that hair that is not stretched has a wider structure chain than hair that is stretched. The measurements agree with the supposition that the human hair consists of a number of parallel chains, suitably linked together, of this nature:



The distance between the two CO groups or NH groups shown in the diagram is 5·1 Ångström units,* and this

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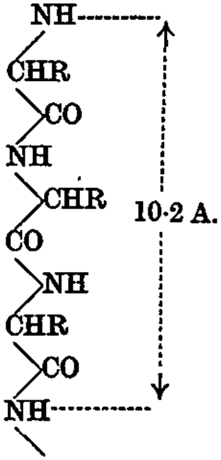
* See Chapter IX for Ångstrom unit.

structure can be stretched a little, and still the attraction between the various groups is sufficient to restore the structure to its original shape. But if the hair is steamed and stretched at the same time, then a straightening of the structure takes place, and gives us the following pattern, in which the distance between the two NH groups, which was 5·1 A., now becomes 10·2 A., and there is no tendency for the groups to recover their original positions, so that if the hair is curled or waved, there is nothing to uncurl it, and the wave is as permanent as the hairdresser can make it.



The keratin in feathers and the scales of snakes is different from that in the hairs of mammals, but is similar to that in tortoise-shell, a fact that is interesting because it has long been known that reptiles and birds had a common origin. Some of the fossil reptiles had wings and some of the fossil birds had teeth.

When we see a team of football players or other sturdy athletes and notice how powerful they are, it seems strange to think that their bodies are mainly composed, to the extent of about 80 per cent., of water contained in minute, thin-walled cells, a spongy mass of material that seems unlikely to be capable of strength. On the other hand, the molecules of water consist of a number of small nuclei of hydrogen and oxygen atoms separated from the little electrons that hold the system together by considerable intervals, and if we consider the constitution of the strongest steel it also consists of small nuclei of iron and carbon atoms separated by similar intervals and held together by similar electrons. Of course the bones in the body are hard substances, but although they contribute to the stability, they do not add to the energy that enables a man to jump six feet high, or to lift half-a-ton from the ground, or to throw a cricket ball a hundred yards. All this force comes from small cells, with walls that are not even air-tight, filled with a watery fluid.

Some of the vegetable fibres are also very strong, even strong by comparison with our metals; thus the strongest fibres of cotton, wool, and linen have tensile strengths as shown in the following table, which are not much inferior to the tensile strengths of some of the metals. In this table are also included silk fibres and artificial silk fibres.

Table of Tensile Strengths.

Material.	Tensile Strength in Kilogrammes per square millimetre.
Aluminium . .	10 to 40
Copper . . .	20 to 50
Cotton . . .	28 to 44
Iron . . .	34 to 50
Silk . . .	35 to 44
Artificial silk . .	17 to 22
Steel . . .	50 to 160
Flax . . .	60 to 110
Ramie . . .	70 to 80
Hemp . . .	80 to 92

The proteins form an essential part of our diet, for our bodies contain many parts that are essential to our health and are composed wholly or partly of proteins. Many of these parts of the body are continually wasting, and the wastage must be made good. Many of the amino-acids that are needed in this process of restoration cannot, it seems, be synthesized in the human body: they must be brought in ready made, made by other animals or by plants, and forming part of our food. The proteins in our food are broken up by the juices of the stomach and intestine into amino-acids small enough to penetrate the walls of the blood-vessels and other vessels in the body. The amino-acids can re-combine with each other in the fluids and tissues of the body, and so keep up a steady source of proteins in all those many muscles, glands, and other parts of the body that are built up of proteins. Besides replenishing the amino-acids in the system, a good deal of the protein we eat is oxidized by the oxygen in the blood, and helps to keep our bodies warm and to supply us with energy.

CHAPTER XX

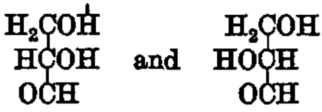
SUGARS, STARCH, AND CELLULOSE

In this chapter we propose to deal with a group of substances of great importance and interest in plants. The group includes a large number of different varieties of sugar; it also includes starch and cellulose.

There are many varieties of sugar, but very few of them are familiar household substances. One of these—cane-sugar—is to be found on almost every breakfast-table and tea-table; whether it is prepared from the sugar-cane or from the beet root, its chemical properties, its taste, and its crystalline form are the same. There is another kind of sugar, called lactose, that is found in milk, and is a constituent of many infant foods. It is not so sweet as cane-sugar, but is more suited to the infants' digestion. Another kind of sugar is called glucose; it is easily fermented so as to form alcohol, and is used in large quantities in the brewing industry.

Malt contains a sugar called maltose; honey is a mixture of more than one kind of sugar; grape juice and some other fruit juices contain another kind of sugar called fructose, and there are probably a hundred different sugars that can be obtained from various plants, but very few of them are sufficiently sweet and sufficiently plentiful to be of interest to the average housekeeper.

The sugars are compounds of carbon, hydrogen, and oxygen, and the simpler varieties have in general a few carbon atoms, the same number of oxygen atoms, and twice as many hydrogen atoms. Several of the more complicated sugars are formed by the combination of simpler ones with perhaps some little additional modification. The very simplest sugars have the formula $C_3H_6O_3$; the three carbon atoms are united together in a short chain; one carbon atom is attached to a group of OH and two hydrogen atoms, one carbon atom (the middle one) is attached to a group of OH and one hydrogen atom; the third carbon atom is attached to an oxygen atom and a hydrogen atom. There are two ways in which such groups may be arranged, and the chemical properties of these two substances will be very similar; they will, however, differ from each other in their optical activity and in their behaviour in fermentation. These two substances can be represented by these two formulæ:



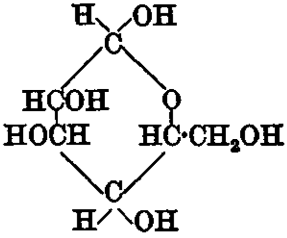
$$\begin{array}{l} H_2COH \\ \;HCOH \\ \;\;OCH \end{array} \quad \text{and} \quad \begin{array}{l} \;\;H_2COH \\ HOCH \\ \;\;\;OCH \end{array}$$

If we look casually at these two formulæ, we might think there are other possible varieties, but if we consider how the atoms are arranged in space—and this is the only safe course to pursue—we shall find there are really only two varieties. Now, these two substances each contain a carbon atom, the middle one, that is attached to four different groups or atoms, *i.e.*, (1) H_2COH, (2) OH, (3) H, (4) OCH. All substances containing such a carbon atom are optically active and can cause a rotation of polarized light. One of the substances whose formulæ we have given above will rotate to the right, the other one to the left, but almost all the sugars that occur in nature are right-handed; animals and plants do not usually make the left-handed varieties, nor do they feed on them or make any use of them. Yeast, for instance, does not ferment the left-handed sugars.

If we consider a sugar containing four carbon atoms, we have to add a H—C—OH group onto each of the two sugars mentioned above, and we can do this in two ways:

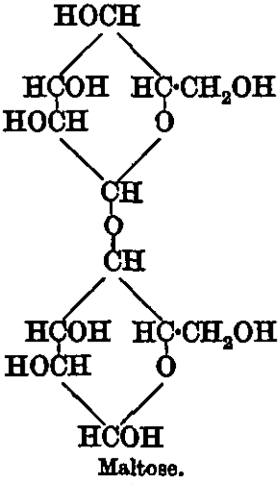
(i) by adding a $H—C—OH$ group, and (ii) by adding a $HO—C—H$ group. There will accordingly be four different varieties of the sugar $C_4H_8O_4$ and eight varieties of the sugar $C_5H_{10}O_5$ and sixteen varieties of $C_6H_{12}O_6$. This last is a very important group, and the whole sixteen varieties have been found or prepared by chemists.

In the group of sugars with six carbon atoms there is generally a closed ring, consisting of four carbon atoms and one oxygen atom, or five carbon atoms and one oxygen atom. For instance, the constitution of glucose is represented by this formula:



Glucose.

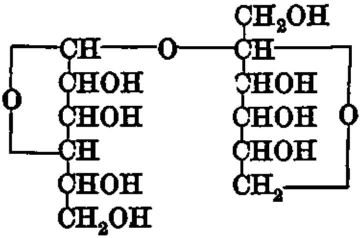
Maltose, the sugar first present in malt, is converted into glucose in the process of brewing, and the glucose is fer-



Maltose.

mented by the yeast, so as to produce alcohol, carbon dioxide, and water. We might guess from this that maltose is closely related to glucose, and in fact it is a combination of two of the glucose molecules connected by an oxygen atom. It has the constitution given on page 218.

It hardly seems necessary to put here the formulæ for many of the other sugars; there are scores of them, some of them containing glucose rings, some fructose rings, and some other sorts of rings. Perhaps the ordinary sugar in our sugar-bowls may be made an exception. It is a combination of glucose and fructose with this constitution:


Fructose portion. Glucose portion.

If this common sugar is heated with water containing a little acid, it is converted into a mixture of glucose and fructose, each of which has the formula $C_6H_{12}O_6$.

Not only does glucose occur in many flowers and fruits; compounds of glucose are also found in the stems, bark, leaves, and fruits of many plants and trees. Many of these compounds are crystalline bodies with a bitter taste, and some of them are useful drugs. Madder, which was formerly of great importance as a dyestuff, is a compound of glucose and a substance called alizarin. These compounds are commonly known as glucosides; one of them, called amygdalin, is found in bitter almonds and in the kernels of apricots, peaches, and plums. Amygdalin is a compound of glucose, prussic acid, and another substance, and it is not difficult to prepare prussic acid from it. Many other plants—in particular the birds'-foot trefoil, Lotus corniculatus, and the wild white clover, and flax or linseed—contain glucosides which easily yield a proportion of prussic acid. This acid is a deadly poison when taken in any quantity, but in a very minute quantity it is probably, like strychnine and other poisons, a tonic or stimulant. It is said that the fattening property of linseed cake is partly due to its very small proportion of prussic acid, and that pastures containing birds'-foot trefoil and wild white clover are valuable partly because of the small proportion of prussic acid in these herbs.

We do not know exactly how plants make the various sugars, but it is certain that, under the influence of light and stimulated by the green chlorophyll, the plant takes carbon dioxide from the air and water from the soil—possibly from the air also—and makes sugar from these ingredients. Plants can also convert starch into sugar; chemically starch is a very complicated sugar, and it is used by the plant as a store of raw material to be drawn upon when need arises. If a chemist wished to make such substances, he would make the simplest sugars first and try to combine these to make the more complicated ones, ending up with starch. The plant, on the contrary, has no plan or fixed intention; its actions are automatic and depend merely on the conditions that exist. The raw materials, CO_2 and water, are easily available, and the plant juices and green leaves assist in the operation; when the time is ripe and the temperature is sufficiently warm, the various atoms combine together to form starch, or complicated sugars, or glucosides, or simple sugars as nature ordains; it is probably as easy for nature to make the complicated compounds as the simple ones.

There is a compound intermediate between sugar and starch that is called glycogen; it does not occur in plants but is of common occurrence in the higher animals, and is stored up in the liver and elsewhere as a reserve for the production of heat and energy. Glycogen is an aggregate of glucose rings, a chain of about a dozen such, and in the body of the animal it easily breaks up so as to form glucose.

Maltose is a combination of two glucose molecules; starch is an aggregate of many maltose molecules in long chains. We do not know how many maltose molecules there are in these chains; there may be twenty-five or a hundred, or two hundred, or even more. We need not suppose it is a fixed number; there are different varieties of starch, and the differences may depend on the length of the chains. Starch usually contains a very little phosphorus and silicon, but these can be regarded as impurities.

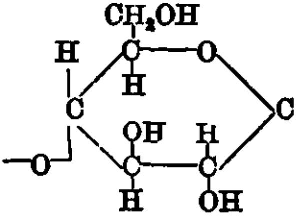
Starch is the main constituent of rice, flour, potatoes, and many other foods. It forms an important part of acorns, chestnuts, onions, and crocus bulbs, and is found in many other roots and seeds.

When starch is mixed with water to which an acid is added, it is gradually converted into glucose, and the same thing happens when we eat a starchy food such as bread, porridge, or rice-pudding. The acid juices in the body convert the starch into sugar in the stomach. A rather similar action takes place when an unripe apple is allowed to ripen either on the tree, or when stored in a cupboard.

There is a substance somewhat similar to starch called inulin; this is the main constituent of the tubers of the *Jerusalem artichoke*, and it is also found in salsify and some other vegetables. It is an aggregate not of the glucose rings that are found in starch, but of fructose rings like that illustrated on page 219, consisting of four carbon atoms and one oxygen atom, with other groups or atoms attached. Many plants that die down in the winter store up in their roots or bulbs a quantity of starch (occasionally inulin) sufficient to act as a raw material from which to make the young leaves and stalks that push above the surface in the early spring.

Long books have been written about the chemistry of sugars and starches, but we are concerned only with the general principles, and not the details. We must, however, spare a little time to a consideration of cellulose.

Cellulose is another aggregate consisting of long chains, each link of which has this constitution :



The number of links in the chain is not definite, and is very large. There are many chains lying alongside each other, and there is a chemical attraction between two adjoining chains, so that the whole aggregate is firmly bound together chemically. Cellulose forms the principal part of the skeleton or structure of plants; the tough fibres in the stalk and leaves are mainly cellulose, and the wood of our trees is composed of a substance that is similar to cellulose. Such vegetable fibres as cotton, flax, and hemp are nearly pure cellulose. When wood-pulp is treated with chemicals it is mainly converted into cellulose, and the paper used for our newspapers and books consists of cellulose. Cotton and thin rags are used for making the finer kinds of paper, and such paper is a very pure cellulose.

Cellulose, as mentioned on page 34, is the foundation of artificial silk, celanese, viscose, and so on. A diagram of its chemical constitution is given on the same page.

The chemical processes used by plants and animals to build up complex substances like cellulose and sugars from simple substances such as carbon dioxide and water are stimulated and controlled by delicate substances called "enzymes." Speaking generally, an enzyme, and one special enzyme, must be present for each chemical action. Enzymes are treated in a later chapter, but even at this early stage their existence may be mentioned and remembered. No doubt the activity of the various enzymes in plants depends on the temperature, the season of the year, and the nature of the plant which it has inherited from its ancestors.

The spring and summer are periods when the sugar-promoting enzymes and the cellulose-promoting enzymes are busily engaged. Probably the starch-promoting enzymes are more busy in the autumn. In many cases the leaves fall, the woody branches may persist, the others wither and fall with the leaves. In this country and in America, in October and the early part of November, the trees are glorious with brilliant reds, oranges, and browns. Why is this? The beauty and poetry of the autumn foliage are not lessened if we understand something of the mechanism that brings about the changes that appeal so strongly to us. The leaves of our shrubs and trees contain compounds of glucose—the glucosides that we have mentioned. In the late autumn, when the leaves have served their purpose and outlived their usefulness, the green chlorophyll breaks up and disappears. For six months it has been useful in assisting the conversion of carbon dioxide and water into sugars, starch, and cellulose. Now its labours are over. The leaves are full of glucosides no longer required; these break up, and in doing this they form colours of singular beauty. There is a great class of glucosides called the tannins, complicated compounds of glucose and gallic acid, an acid first obtained by Scheele from oak-galls. Some of these tannins are brilliant reds and oranges; you can see them not only in the autumn foliage, but also in the bark of the cherry tree and the old bark of the red-currant bushes. The red colours of the autumn foliage are not all tannins, some of them are anthocyans, compounds described in Chapter XXVI. Other glucosides produce black, brown, and yellow pigments. Finally the leaves and soft parts of the plants fall to the ground. Crowds of slugs, insects, bacteria, moulds, and germs of every kind attack them; the water that accounts for perhaps three-quarters of their weight evaporates; the residue remains, and is gradually incorporated into the numerous organisms that inhabit the top few inches of the soil. And in the next year the process begins again, as it has done for millions of years in the past and will do for millions of years in the future.

CHAPTER XXI

RESPIRATION AND DIGESTION

WHEN we breathe we take air into our lungs; in this connexion the air may be assumed to be a mixture of four parts of nitrogen and one part of oxygen; the nitrogen is inert so far as respiration is concerned, and undergoes no chemical change; it is the oxygen alone that is of importance. The lungs have a number of small air cavities surrounded by a multitude of tiny blood-vessels, in which the blood is kept circulating by the mechanical effect of the valves of the heart. Our blood is a fluid with countless red corpuscles containing hæmoglobin, a compound of two substances, hæmin and globin. We do not know the exact composition of hæmoglobin, but we do know that of hæmin, which is made up of carbon, oxygen, hydrogen, nitrogen, and iron, combined together as indicated in the diagram on p. 277; globin is a protein, the constitution of which is not exactly known. Hæmin has a constitution somewhat similar to that of chlorophyll, the green colouring matter of many plants whose formula is given on p. 277. Hæmoglobin has the valuable power of easily combining with oxygen and easily parting with the oxygen so combined. It can combine under suitable conditions with one atom of oxygen for each atom of iron that it contains. *Cell walls in animals, like most of the walls of our houses,* are neither air-tight nor water-tight, and when the fresh air in the lung comes in contact with a collection of blood-vessels, some of the oxygen permeates through the thin walls of these vessels and combines with the hæmoglobin.

The normal circulation carries this oxygenated blood in the arteries to the muscles, stomach, intestines, spleen, liver, and other organs of the body, in all of which it finds carbohydrates, proteins, fats, and other substances ready to undergo oxidation. The final products of the oxidation are carbon dioxide and water, and these pass through the wall of the blood-vessel and are carried along by the veins. The carbon dioxide is carried to the lungs, where it escapes through the wall of the vein into the air cavities of the lungs and is breathed out again; the extra water is gradually removed from the blood by the kidneys, stored in the bladder, and finally excreted.

The oxidation of the carbohydrates, proteins, fats, and other substances in the organs of the body gives rise to heat in precisely the same way as the oxidation of coal in a fire does. This heat is sufficient to maintain our bodies at a temperature higher than the usual temperature of the surrounding air. The whole process is automatically controlled, so that if the blood is receiving carbonic acid at an unusually fast rate, the heart is stimulated to pump it quicker to the lungs, and breathing is quicker and deeper. The control is unconsciously directed from a special portion of the brain, where most such controls are to be found.

Every time we contract a muscle there is an oxidation of a carbohydrate contained in the muscle—that is to say, some of the carbon and some of the hydrogen in the carbohydrate unite with oxygen present in the neighbouring tissue. This carbohydrate is glycogen, which was mentioned in the previous chapter. The oxidation of glycogen resulting from the contraction of a muscle gives rise to a certain amount of energy that starts a chain of chemical actions which accompany the muscular actions; further information about these is given later. A human being engaged in violent exercise is therefore making more carbon dioxide and water in the blood, causing the heart to beat more frequently and the lungs to work more efficiently. We know that work and heat are related to each other in a definite manner, and that the more work the body or any other engine is required to do, the more fuel you must give it and the more oxidation of the fuel must take place.

It might be thought that immediately after a good square meal, when the stomach is pleasantly supplied with beef, and potatoes, and apple-pie, and bread, and cheese, and beer, there would be a rapid increase of combustion and a rise in temperature. This is not the case, for although such food begins to undergo chemical change from the very moment it enters the body, the process of digestion is a slow one, usually taking many hours, and the oxidation that gives rise to an increase of temperature is in the case of most foods a late stage in the process rather than an early one.

It is curious how uniform is the temperature of the human body, or a sheep's body, or the body of most other mammals, in a state of good health. Various controls prevent the oxidation from taking place too fast; they prevent the temperature of the body from rising above the normal. In very many diseases something happens which upsets the equilibrium of the body, and in particular some of the more or less automatic systems of control; the result is a more rapid oxidation of the tissues of the body, and of the food, and the products of the food in the course of its digestion; the effect of this is easily detected by a rise in temperature shown by the clinical thermometer.

We have already referred to the oxidation of glycogen in the muscle when the muscle is contracted; this is part of a rather complicated story that we will try to explain as simply as possible. We get a sort of alternation of chemical actions, the one reversing the effect of the previous one, in the mechanism and chemical behaviour of our muscles, just as we get an alternation of chemical action in the lead accumulator. These muscles contain about 80 per cent. of water, about 15 per cent. of proteins, about 1 per cent. of glycogen, and in some circumstances about ¼ per cent. of lactic acid, and a smaller percentage of a phosphate of a sugar and of a phosphate of creatine (a substance derived from protein). The muscle will also contain many enzymes—obscure substances which act as catalysts, starting or assisting chemical changes—and the muscle may also contain a little fat. The proteins, glycogen, and fat are all capable of being oxidized when sufficient oxygen is present in the blood-vessels, and normally the muscles are slowly taking in oxygen and giving up carbon dioxide.

During exercise the muscles are frequently contracted, and muscular contraction is found to be associated with the production of lactic acid obtained from the breakdown of a portion of the glycogen. This production of lactic acid continues so long as the exercise continues; but when the muscle is allowed to rest, the lactic acid itself undergoes oxidation, one-fifth of it being converted, not necessarily directly, into carbon dioxide, the remaining four-fifths being converted back again into glycogen.

These alternations of production of lactic acid and of glycogen involve a gradual reduction in the quantity of glycogen present, and this carbohydrate has therefore to be regularly restored to the tissues of the body, and it comes indirectly from the foods that we eat. There are other reversible chemical actions that take place in muscles. Thus, during exercise the compound of creatine and phosphoric acid breaks up, forming separate quantities of creatine and phosphoric acid; during a period of rest or recovery the compound is again formed.

Similarly a compound called adenyl pyrophosphate breaks down in exercise and is rebuilt during rest from its constituents: adenine, ribose, and phosphoric acid.

The digestion of breakfast or any other meal is a process too complicated for our consideration; we will choose something simpler. Let us assume that a sturdy youth consumes a pound of muffins. A lady of our acquaintance tells us emphatically that this is ridiculous, but she has forgotten the well-known case of the man who ate three shillingsworth of crumpets at a sitting; the details are given in *Pickwick Papers*, Chapter XLIV. As our sturdy youth masticates the morsels, the salivary glands, in response to a message from the brain, pour into his mouth the needful quantity of saliva containing the enzyme, ptyalin. which gradually converts the starchy parts of the muffin into sugar. The well-chewed mass passes down the gullet into the stomach, where it encounters the gastric juice which plays no part in converting the starch into sugar, but it does play a part in the digestion of other substances, as we shall describe later. The effect of the saliva on the muffin in the stomach is a conversion of most of the starch into sugar.

The cell-walls of the stomach and intestines do not permit very large molecules, like those of starch or the most complicated sugars, to enter the blood-vessels, but they do permit the smaller molecules of the simpler sugars to enter. The human body has a supply of complicated carbohydrate in the stomach, and it wishes to store up a complicated carbohydrate in the liver, but the molecules are too large to travel. The problem is solved in the simplest and most obvious way: in the small intestine the complicated carbohydrate is broken down into simple sugars which can penetrate the small orifices; these find their way into the small blood-vessels, then into the portal vein, and so to the liver; there they are combined together to form the complicated carbohydrate, glycogen, in which form they are stored up to be drawn upon as required.

The supply of the simple sugar, almost the whole of which is glucose, in the blood is kept very constant, about 0·1 per cent. In the disease diabetes the mechanism of the sugar control breaks down and the proportion of glucose in the blood becomes excessive, especially after a meal in which sugar is included. The control of sugar in the blood is, in healthy people, regulated by " insulin," a substance of protein constitution secreted by the pancreas. If the pancreas is diseased or removed, the control is not effective; the proportion of sugar in the blood rises abnormally, and in acute cases the patient dies. A daily injection of insulin into the blood may enable the patient to live comfortably and work regularly for many years.

When the blood reaches the lungs, the sugar is oxidized, as has been already explained, in accordance with this equation:

$$\underset{\substack{\text{One molecule}\\\text{of sugar.}}}{C_6H_{12}O_6} + \underset{\substack{\text{Six molecules}\\\text{of oxygen.}}}{6O_2} = \underset{\substack{\text{Six molecules}\\\text{of carbon}\\\text{dioxide.}}}{6CO_2} + \underset{\substack{\text{Six molecules}\\\text{of water.}}}{6H_2O}$$

Assuming that half the pound of muffins was starch, it will in course of its gradual oxidation be converted into about three-quarters of a pound of carbon dioxide and about three-tenths of a pound of water. The carbon dioxide occupies a volume of about six cubic feet, and it will take several hours to be exhaled in the breath. The water, occupying a volume of about a quarter of a pint, slowly finds its way from the blood, through the kidneys and into the bladder.

Let us now consider the digestion of butter or some other fat. Butter contains about 10 or 11 per cent. of water, and the rest is mostly fat, a mixture of compounds of glycerine with fatty acids; these substances have already been described on p. 39.

The names of these fatty acids need not trouble us at the moment; the important thing is that each molecule of fat contains more than a hundred atoms, and very likely there are aggregates of molecules to be considered as well. In any case just as the units of starch are too large to go through the cell-walls in the body, so are the molecules or aggregates of butter-fat. The soap-maker boils together fats and alkalis and obtains soap and glycerine; the human body does the same thing, but at a much lower temperature. The gastric juice and bile contain sodium compounds and an enzyme called lipase; the effect of these is to break up the great fat bodies into small substances—glycerine $C_3H_8O_3$, and the fatty acids, palmitic acid, oleic acid, and so on. The fatty acids act upon the sodium compounds making soaps which, with the glycerine, are small enough to get through the wall of the intestine, and having done this a considerable proportion of the glycerine and the soaps react with each other to form new fats, not all identical with those present in the butter. The new fats travel in the juices in the lymphatic glands and are stored in various places in the body, where they are either burnt (oxidized) immediately or stored as a food reserve.

The fact that the animal selects particular parts of the fats it has swallowed, and not all, for re-conversion and storage, accounts for the difference between goose fat, mutton fat, and bacon fat.

We all know that carbohydrates and fats are not sufficient for our diet; we must have proteins as well; without these the animal would not receive enough nitrogen.

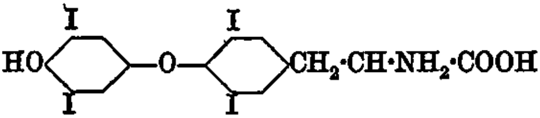
Beef and mutton contain from 10 to 20 per cent. of proteins, fish rather more, milk about 3 per cent., butter about 1 per cent., cheese about 25 per cent., some fruits about 1 per cent., chocolate about 13 per cent., beer about ½ per cent., tea and coffee none.

When meat is eaten, the proteins find their way into the intestine and, like the other substances we have considered, the molecular chains or aggregates are too large to proceed through the cells that form the wall of the intestine; the pancreatic juice and the intestinal juice together break down the proteins to form amino-acids, and these are absorbed in the lower part of the small intestine and enter the portal vein, and so are carried to the liver. They are the main supply of the nitrogen required to build up our muscles, our blood, and the other nitrogenous constituents of our body. But we take in a far larger quantity of proteins than is necessary for this purpose; all the common foods except sugar contain proteins, and only about 10 or 15 per cent. of the nitrogen of the proteins we swallow is required for keeping up the supply of nitrogen in the body; the rest of the nitrogen is converted into urea, $CO(NH_2)_2$. The urea finds its way into the blood, and thence into the bladder.

All the chemical reactions associated with respiration, with digestion, and indeed with all the chemical reactions occurring in the body, are controlled automatically. There is normally more than one control for each reaction. This, no doubt, is a form of safety mechanism; if one control breaks down, there are others that can carry on the work, perhaps not quite so efficiently. One of these controls is provided by the thyroid gland, which is situated in the throat at the sides of the windpipe.

Medical men have been acquainted with this gland for nearly three hundred years, but have not understood its function in life for more than about fifty years, and the mechanism of its structure and working has not been known for as long as ten years.

If the thyroid gland is not in a condition to work properly, there are two ways in which this may become manifest: the disease goitre, or the condition of imperfect development of the body and brain called cretinism. One of the symptoms of goitre is a swelling of the neck, recorded two thousand years ago, and a traditional remedy for goitre was to swallow the ashes of burnt sponge! This remedy was recorded so long ago as the year 1210 A.D. Shortly after iodine was discovered in 1812 a doctor in Geneva named Coindet guessed that the ashes of burnt sea-weed, from which iodine was prepared, might resemble the ashes of burnt sponge, and that possibly iodine was present in both, and might cure goitre just as well as burnt sponge. He therefore tried iodine as a cure for goitre, and was immediately successful. Shortly afterwards a Scotsman, Fyfe, proved that the burnt sponge did contain iodine. About a hundred years later Kendall prepared from thyroid glands a crystalline substance called thyroxine containing about 65 per cent. of iodine. In 1925 Dr., now Professor, Harington, proved that thyroxine has this constitution:



and in the following year he prepared a substance with this constitution by chemical means in his laboratory, and found it to be identical with the thyroxine obtained from the thyroid gland. Since then thyroxine has been prepared on a commercial scale and used as a cure for goitre. But although this is effective, it is not so effective as the natural thyroid gland, and quite recently it has been shown that the thyroid gland contains a compound of thyroxin with diiodotyrosine. Indeed, thyroxine is formed in the gland, it seems, by a condensation of two molecules of diiodotyrosine, which may be regarded as the parent of thyroxine. And it has been proved that diiodotyrosine is present in sponges and certain corals. The thyroid gland, which exercises so useful a control over our growth and health, cannot exist unless a small quantity of iodine is present in the food, and in fact this small quantity is usually obtained from the water we drink or in which we boil our mutton and potatoes. A district in which the water contains no iodine will be one in which the plants also contain no iodine, and goitre will be found to be prevalent. The disease will be prevented or cured by the addition of minute quantities of iodine or a compound of iodine to the water drunk by the inhabitants.

It is quite obvious that plants and animals, even the very simple ones, can make an enormous variety of chemical compounds, some of them not very complex, but some so complex that the skill of chemists, which is very considerable, cannot yet find out their structure. Many of these complicated compounds can be made by chemists in their laboratories, many cannot be made. Most of the sugars made by plants can also be made by chemists, but the latter cannot make starch, or glycogen, or cellulose. The chemist can make indigo as efficiently as the plant can and dibromindigo as efficiently as any shellfish. He can make thyroxine and many of the vegetable alkaloids; he can take nitrogen from the air and make from it ammonia and the simpler amino-acids, but he is unable to make proteins in his laboratory. For many of his chemical experiments he requires high temperatures—that of boiling water, for instance—and for some he requires high pressures—for instance, in the hydrogenation of carbon to make petrol. The plants and animals carry on their chemical processes without the aid of high pressures or high temperatures. At a pressure of 200 atmospheres and at a temperature of 450° C. the chemist can convert a mixture of hydrogen and carbon into petrol—and very good petrol, too—but a kind of pine tree makes excellent heptane, C_7H_{16}, at atmospheric pressure and quite ordinary temperatures. Petrol consists of a mixture of many compounds of the nature of heptane. It is worth while spending a few minutes in considering how the plants and animals contrive their processes: perhaps this is not quite the appropriate phrase to use; there is no conscious effort on the part of the living organism; it makes the chemical compounds because it cannot help doing it; the necessary ingredients are all present, and if the conditions are favourable the chemical action takes place. Just as the chemical actions in the chemical laboratory are often started or encouraged by the presence of a catalyst, so the chemical actions in the living cell are started or encouraged by the presence of an enzyme. The catalysts used by the chemist are usually simple substances—spongy platinum, sulphide of molybdenum, manganese dioxide, and such substances. The enzymes are extremely complicated substances that act as catalysts because some part of their structure is unstable and in the presence of other compounds this part starts a chemical action such as oxidation or the formation of a colouring matter, and once the chemical action is started it spreads possibly over a considerable area.

If we could isolate a number of these enzymes and analyse them, we could probably make them artificially, and how useful they would be! But they are fragile in their constitution, and will not stand the treatment with acids or alkalis, the boiling, and precipitation, and crystallization, and such other treatment as the chemist makes use of to separate them from the other substances present; so most of them remain nearly as mysterious as they were seventy or a hundred years ago. We know where to find them and what special actions they take part in; there is a separate enzyme, generally speaking, for each separate chemical action in a plant or an animal. Each plays its separate part and no other.

We know little of the enzymes which assist digestion and so many other operations. We are not sure that they are chemical compounds; the enzymes are perhaps specially active portions of larger molecules or compounds; we know more of their habits than their appearance or structure. They are responsible for many of the processes of fermentation and of digestion; for the changes of starch into sugar, and of sugar back again into starch, for the fermentation of sugar to form alcohol, for the fermentation of the madder root to form alizarin, for the fermentation of indican to form indoxyl, the parent of indigo, and for countless other changes. We do not know their formulæ, and it would be wearisome if we were to give a long list of them. We will mention a few only, as samples of the sort of work that they do.

Of the plant enzymes there is one called lipase, found in many oily seeds; it is able to break up fats into a mixture of fatty acids and glycerine. Another called maltase is able to break up the sugar that gives the sweet taste to malt into smaller molecules of glucose. One, called invertase, is found in yeast, and it is able to convert cane-sugar into the simpler sugars, glucose and fructose. Emulsin, which is found in the leaves of some trees, is able to produce from a more complex substance small quantities of prussic acid, HCN.

The sundews that we find in boggy places have hairy leaves with a sticky drop at the tip of the hairs. These catch flies, and the leaves emit an enzyme that dissolves all the best parts of the flies and enables the sundews to feed upon them.

CHAPTER XXII

THE VITAMINS

DURING the last twenty years we have become familiar with the idea and the name of vitamins, and this important discovery has undoubtedly done a very great deal to advance our knowledge of diet and nutrition. For a million years or more man has been experimenting with his diet, but he has only recorded his observations for a period of a few thousand years, and has only approached the subject with what we may call any scientific method for a much shorter period.

Originally the savage man had to be content with such food as he could find, and a poor and precarious diet it no doubt often was: shellfish for those who lived near the sea, berries and other fruits in their season, and such wild animals, dead or alive, as he could secure, garnished with herbs of a very indifferent quality. In some of the Scandinavian countries there are immense mounds of shells, the relics of meals of primitive man before he had acquired the art of growing crops or domesticating animals.

It was not until he had achieved these two arts that he had any time for an advance in his civilization; before this period his life must have been a long, weary, and unceasing search for the next meal, and often he must have added to his diet some decayed fish, or green herbs, or red berries that taught him or his descendants a lesson that was never forgotten.

When man became civilized, and grew corn and cabbages, and kept cows and horses and goats, and made himself clothes from skins, and wove coarse garments from wool and vegetable fibres, no doubt new problems arose and new diseases of which we have but a scanty record. The ancient Egyptians attained a high degree of civilization, and one of their early manuscripts recommends ox-liver as a remedy for a strange disease, still found occasionally, that is characterized by inability to see except in a good light and is known as night-blindness. The ox-liver contains nothing in the nature of a drug, and its usefulness depends on its containing something necessary to good health, found in many foods, but not all, so that a diet consisting entirely of the other foods is deficient in a necessary ingredient, and disease results. Other diseases caused by a deficiency of some necessary ingredient have been very common in the past, and are still far too prevalent in countries where the majority of the people are too poor to be able to feed themselves properly. People who are comfortably well-off can afford green vegetables, milk, butter, eggs, and similar luxuries, but there are thousands or millions of people living mainly on rice or maize with an occasional relish of salt fish or salt meat, who are accustomed to a diet with too little variety, and have neither the knowledge how to supplement it nor the money to buy the additional articles necessary to keep them in good health. As the result of research carried out mainly during the last twenty-five years, the knowledge is now very readily available, but still there are vast numbers of people at present so poorly paid that they cannot obtain the small quantities of the extra foods that are required, and they have become accustomed to a variety of diseases caused by a deficiency of diet, diseases often terrible in their consequences and very easily prevented at the expense of a trifling sum each week.

Such diseases are caused by the lack of vitamins, the existence of which became gradually suspected. They have been proved to exist during the last twenty-five years, and some of them have been isolated and their constitutions determined during the last three or four years. We propose to consider the history of the discovery of these vitamins, for a knowledge of their occurrence and properties is of extreme value to the whole of the population of civilized and uncivilized countries.

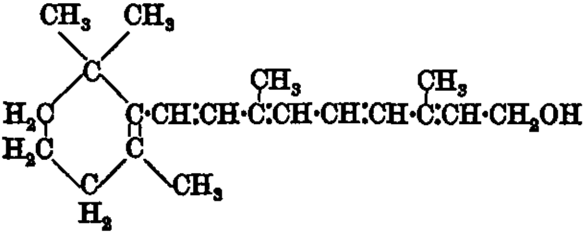
The vitamins are now usually known by the letters of the alphabet: vitamin A, vitamin B, vitamin C, vitamin D, and vitamin E. Each of the different vitamins is associated with some disease in this sense, that unless the diet contains such vitamin the individual will suffer from a special disease, usually easily cured by the addition to the diet of a food containing the vitamin in question.

We will begin with vitamin A, a substance contained in small but sufficient quantities in milk, butter, eggs, many green vegetables, the livers of many fishes and other animals, and very conveniently available in cod-liver oil and halibut oil. People whose diet is deficient in this vitamin may suffer from night-blindness and from a scaly condition of the eyes called xerophthalmia, and, in addition, they have poorer health than they should and they are less able to resist infectious diseases. Young rats deprived of vitamin A in their food fail to grow normally, so that it is probable that it is also necessary for good growth in children. The air we breathe, the water we drink, the clothes we wear, and the rooms and trains we frequent are peopled by innumerable germs of various diseases. Normally the various cells and juices of the body are able to cope with the invasion of these disease germs, and if we are in a good state of health we run very little risk from exposure to them, so that we need not bother very much about the seeds of disease, provided we have the usual powers of resistance. Take care of the soil, and the seeds will take care of themselves! On the other hand, if our diet is deficient in the proper vitamins and our powers of resistance are thereby enfeebled, our bodies cannot prevent the disease bacteria from entering the blood, multiplying rapidly, and giving us a variety of infectious diseases. We have already referred to the fact that the ancient Egyptians recommended ox-liver as a cure for night-blindness, and the same cure for this disease was known to Hippocrates. During the eighteenth century and the first three-quarters of the nineteenth century a number of observations were made by various peoples on the effect of diet on scurvy, beri-beri, and other diseases; experiments were made on dogs and human beings showing that a varied diet was much more useful than a diet containing sufficient carbohydrates, and fats, and so forth, but without the vegetables, milk, and fruit, that we now know to be necessary. The experiments of Sir Frederick Gowland Hopkins, carried out between the years 1906 and 1912, were perhaps the most conclusive.

It had long been known that mammals required certain amounts of carbohydrates (sugar, starch, etc.), as well as fats and proteins (meat, eggs, etc.), for their sustenance, and Gowland Hopkins fed rats on such a diet; the more he purified the carbohydrates, fats, and proteins, the quicker the rats died. When he added to their food a minute proportion of milk, they flourished exceedingly. His paper in 1912 on "Feeding Experiments Illustrating the Importance of Accessory Factors in Normal Dietaries" has become a classic, and the "accessory factors" are what we now call vitamins. Dr. Casimir Funk, a Pole then working at the Lister Institute in London, gave one of them—the one now called vitamin B—the name "vitamine" in 1913, thinking that it was one of the nitrogenous bases called amines. The final "e" was dropped in 1920 on the suggestion of Professor Drummond of University College, London, and the name "vitamin" given to all the substances, then called "accessory food factors." Funk did much more than invent a name for the vitamins; he was a pioneer in their study.

McCollum and Davis in Baltimore, U.S.A., in 1913 and 1914 showed that the essential vitamin we are now considering was dissolved in many fats, such as butter, and they called it Fat Soluble A.

It has been studied very minutely in several countries, and much is now known about it. Vitamin A is a compound whose formula is:



The molecule is half the molecule of carotene, $C_{40}H_{56}$, with two hydrogen atoms and one oxygen atom added. Carotene is an orange-red hydrocarbon, or mixture of very similar hydrocarbons, contained in carrots, in green grass, mountain-ash berries, diatoms, sundry marine algæ, and other plants. The diatoms and marine algæ are the food of small marine animals, which are themselves eaten by small cuttle-fish; these form the food of great fish such as the cod, halibut, and shark, and the livers of these fishes contain an abundant supply of vitamin A. It is a singular thing that once the vitamin A is made, probably by some small marine animal, it seems to persist; it is stored up first in one animal's liver and then in another's, and the older the cod or halibut is the greater the proportion of vitamin A it contains.

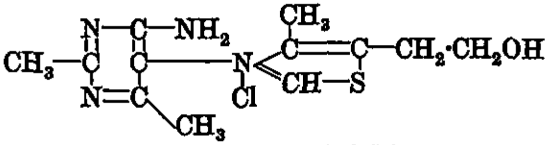
Vitamin A is finally stored in the human liver, which in well-fed beings has a supply sufficient to last for a few months.

Let us consider the carotene made by grass and other land plants. The plants are eaten by cattle and some of the carotene finds its way into the milk of the cow, giving it a slightly yellowish colour; some of the carotene is converted into vitamin A in the liver of the cow and is found in the milk, some of the carotene is converted into vitamin A and is stored up in the liver. If hens are allowed to run on a field, they eat a quantity of green herbs, and the carotene finds its way into the yolk of the eggs and gives them their colour. As a general rule, the richer the soil is, the more carotene the grass will contain; so if a pasture is properly fertilized with sulphate of ammonia, the grass will be greener, and will also contain more carotene, and there will be more carotene and more vitamin A to be recovered from the cattle and the poultry fed there.

McCollum called attention to the water-soluble vitamin B, now shown to consist of a mixture of vitamins. It is certain that there are at least three distinct B vitamins, probably there are four or more, but until these have been isolated in a practically pure state we cannot be more definite. These vitamins are called B_1, B_2, B_3, and so on.

Vitamin B_1 is a substance that is found in the outer covering of cereal grains, in beans, cabbages, turnips, tomatoes, milk, yeast, and several other animal and vegetable foods. If human beings are given a diet that contains none of these foods, they are very apt to suffer from the dangerous disease beri-beri. In the Japanese Navy fifty years ago the sailors were fed upon rice polished so as to remove all the outer covering, and sometimes nearly a third of the sailors were on the sick list, suffering from beri-beri. Admiral Takaki between 1878 and 1888 was able, by adding green vegetables to the diet, to reduce the disease to negligible proportions. The disease and the means of preventing it and curing it were further investigated by Pekelharing and Winkler in 1893, and by Eijkman in 1896 and subsequent years, and they confirmed the experience of Admiral Takaki. Beri-beri has been very prevalent in the Philippine Islands and not uncommon in Newfoundland, where some of the poorest of the population have been accustomed to a diet of white bread and tea. The disease could easily be driven out of existence, but many Eastern peoples much prefer polished rice to unpolished rice, and do not grow green vegetables; moreover, some other people can afford in the winter a diet of white bread and tea, but cannot afford green vegetables (see Plate VII).

Crystalline preparations of vitamin B_1 have been made by several teams of workers in Britain and other countries. The formula of its chloride is believed to be as follows:



Vitamin B_1. $C_{12}H_{18}ON_4S$.

Just as vitamin B_1 is associated with the disease beri-beri, so vitamin B_2 is associated with the disease pellagra, common in some of the south-eastern European countries and in the cotton-growing districts of the United States. Before the Great War there was a very bad outbreak of pellagra in Mississippi and Carolina; it was studied by Goldberger for several years, and he found that the people who suffered from pellagra in those States lived principally on maize, and that the disease was cured and prevented by the addition to their diet of yeast or milk, eggs, tomatoes, or other foods.

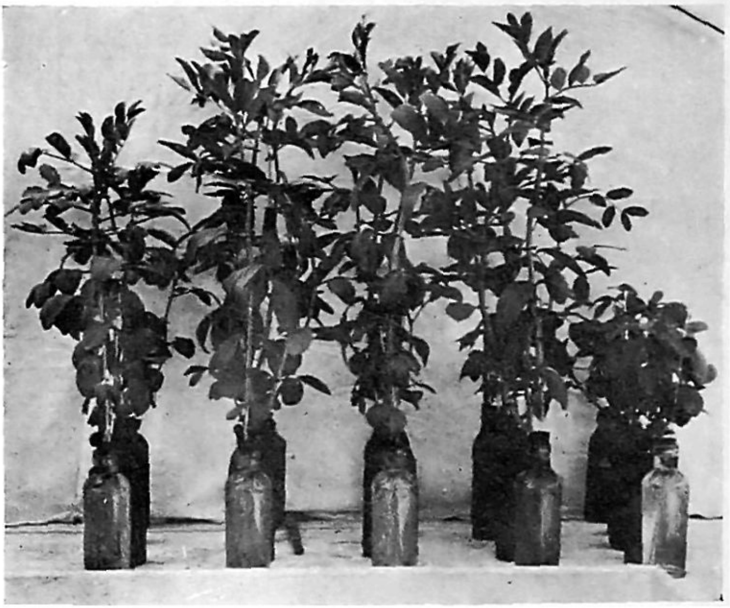
Vitamin B_2, like the original vitamin B, has now been split up into more than one constituent. One of these is effective in preventing pellagra, the other is necessary for the proper growth of young animals. This latter substance has been shown to be identical with lactoflavine, which has the formula $C_{17}H_{20}N_4O_6$, and is one of a group of naturally occurring colouring matters. Lactoflavine has been obtained in crystalline form.

Vitamin C is found to prevent and to cure the disease scurvy, formerly so prevalent in almost all navies. Cartier in 1535 cured his men who were suffering from scurvy by giving them a decoction of green shoots. Hawkins at the end of the sixteenth century said he could give an account of 10,000 seamen killed by scurvy; Anson in 1740 lost four-fifths of his men from it. Captain Cook prevented scurvy by giving his men infusions of germinated barley and of cabbage. A British naval surgeon, Lind, studied the matter very carefully, and wrote a *Treatise on Scurvy*, published in 1752. In this he described how in 1747 he took twelve scurvy patients on board his ship at sea; he fed them on water-gruel, fresh mutton broth, puddings, boiled biscuit, barley, raisins, rice, and so on. To two of the twelve he gave a quart of cider a day; two others received twenty-five drops of elixir of vitriol three times a day; two others received vinegar; two others about half a pint of sea-water a day; two others had two oranges and one lemon each a day, and the remaining two had a mixture of garlic, mustard seed, balsam of Peru, gum myrrh, and other such drugs. The two who were given the oranges and lemons speedily recovered; the others derived but little benefit from their special treatments.

In 1795 lemon juice was made compulsory for naval ratings in the British Navy, and scurvy disappeared from it. It occurred only in this century quite needlessly, in some Arctic and Antarctic expeditions and during the Great War, but is easily cured and prevented by orange juice, lemon juice, the juice of potatoes and swedes, and germinating beans and cereals. All these contain vitamin C, a substance that has been investigated recently by numerous workers, who have shown it to be identical with a substance previously known

[L. Harris.

RATS FED ON (*left*) WHITE FLOUR (CONTAINS NO VITAMIN B_1), (*right*) WHOLE MEAL (CONTAINS THE VITAMIN)

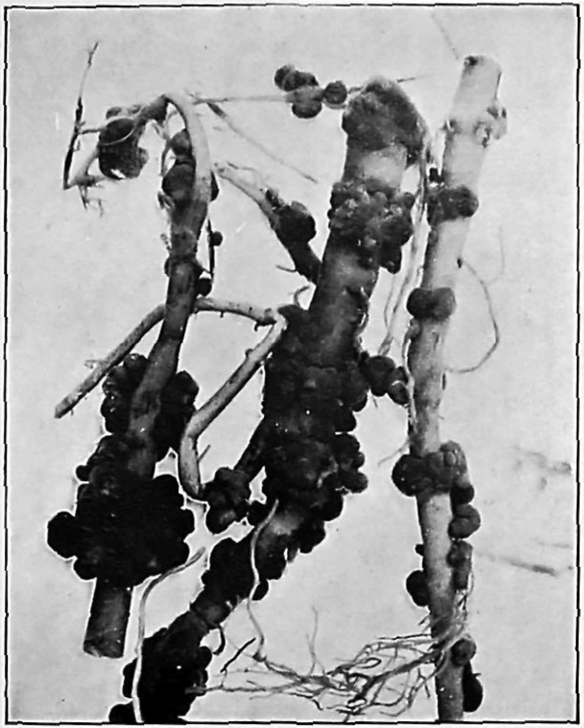


[E. J. Russell.

INFLUENCE OF BORIC ACID ON DEVELOPMENT OF THE BROAD BEAN IN CULTURE SOLUTION

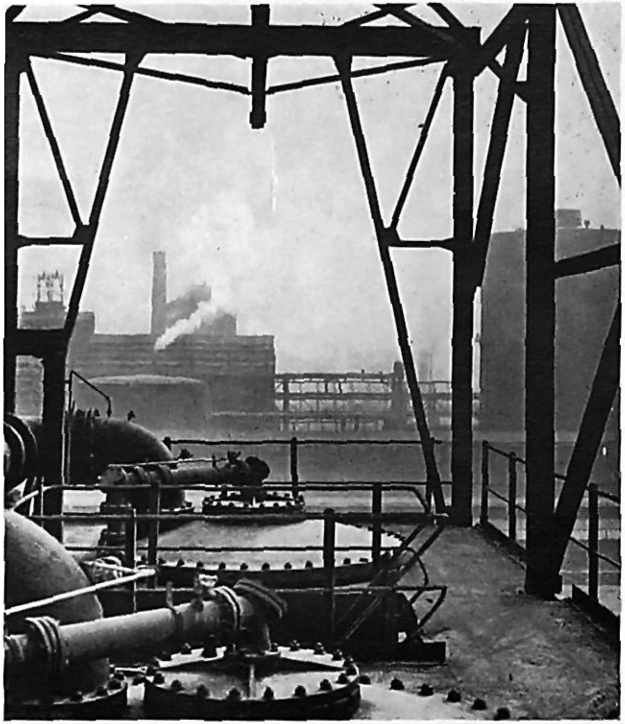
The four to the left had traces of boric acid added to the culture solution.

PLATE VIII



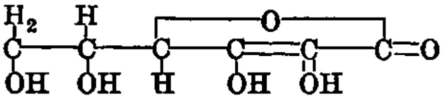
[*G. J. Fowler.*

ROOT NODULES OF PEA



[*Imperial Chemical Industries Ltd*

CARBONATING TOWERS IN THE MANUFACTURE OF SULPHATE OF AMMONIA to exist in horse-radish, and then called hexuronic acid. This has now been renamed ascorbic acid, and it has been shown to be a simple substance related to the sugars and having this formula:



$$\overset{H_2}{\underset{OH}{C}}-\overset{H}{\underset{OH}{C}}-\underset{H}{C}-\underset{OH}{C}=\underset{OH}{C}-C=O$$

Ascorbic acid has been synthesized by purely chemical means, and the synthetic ascorbic acid has been shown to be able to cure scurvy in guinea-pigs. This was the first example of the synthesis of a vitamin.

Cod-liver oil contains other vitamins in addition to vitamin A, and we must not attribute all its good qualities to that vitamin alone. Dr. Edward Mellanby, working at Sheffield, in the years immediately after the late War showed that if puppies are fed on a diet containing no fats they will suffer from rickets. The addition of fats to the diet cured the disease. He suggested that rickets was caused by lack of the " Fat-Soluble A " factor, but showed that the growth-promoting properties and the properties that prevented rickets did not always run closely together. This theory as to the cause of rickets was radically different from that put forward by Findlay and his colleagues in Glasgow, who found that defective hygiene, want of exercise, and general lack of an outdoor life, were responsible for the many cases of rickets in that city. Furthermore, it had been shown by other workers that ultra-violet light and sunlight were both effective in curing rickets. Here were two well-authenticated, yet seemingly contradictory theories, which must have offered little hope of any compromise. Yet they are both the truth, and how this was shown to be the case is an interesting story. McCollum in America showed that by oxidizing cod-liver oil, its power to cure xerophthalmia was destroyed, but that it still cured rickets, thus showing that there were two different vitamins in cod-liver oil, and that, in addition to vitamin A, which will cure xerophthalmia (night-blindness), there is another vitamin which will prevent or cure rickets.

Hume and Smith, two workers at the Lister Institute, kept rats on a diet that was deficient in fats and exposed the cages in which the rats lived, but not the rats themselves, to the rays from a mercury vapour lamp. These rats grew normally; Hume and Smith concluded that the irradiated air caused this effect, but later they showed that the rats had preserved their health by eating the irradiated sawdust in their cages. Other workers showed that the irradiation of foodstuffs that were normally not active in curing rickets would make them active, and from this time progress in solving the puzzle was rapid. Rickets occurs because some special substance, that we now call vitamin D, is absent from the food. If the food is irradiated by rays from a mercury lamp, or by sunlight, this vitamin D may be produced in the food, obviously by a change taking place in some substance previously existing in the food. This substance has since been isolated, and it is called ergosterol; it is commonly present as a constituent of foodstuffs, and when eaten it finds its way into the blood. The blood flows freely in the small vessels that lie near the skin, and in sunlight the ergosterol in these small vessels changes into vitamin A. Vitamin D is now manufactured on a commercial scale by subjecting ergosterol, obtained from yeast, to the action of ultra-violet light. We can buy this vitamin, under the name of "calciferol," in a crystalline form in many shops.

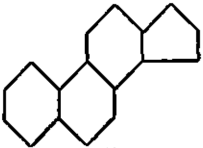
Vitamin E appears to be necessary to ensure fertility in both male and female animals. Although it was discovered more than ten years ago, its structure—if it is a simple substance—is not yet known, though it is related to ergosterol.

Perhaps a little summary of the vitamins in the form of a table will be convenient.

Vitamin	Soluble in	Contained in	Properties.
A	Fat	Milk, butter, eggs, cod-liver oil, etc.	Necessary for growth and anti-infective.
B_1	Water	Cereals, tomatoes, yeast.	Prevents beri-beri.
B_2	Water	Yeast, milk, eggs.	Prevents pellagra and necessary for growth.
C	Water	Green vegetables, oranges, lemons.	Prevents scurvy.
D	Fat	Fresh fruits and vegetables, cod-liver oil.	Prevents rickets.
E	Fat	Green leaves, cereal embyros.	Prevents sterility.

In addition to the vitamins we have mentioned, one or two others have been described of which the nature and functions are not very certain. Among these is one recently discovered by Professor Szent-Gyorgyi, which seems to be one of a well-known group of vegetable dyes, the flavones, and closely allied to the anthocyans described on page 280. It will be of interest if this group, which is of importance in the vegetable kingdom, should also be of importance in the life of the higher animals. But there are other instances, and all the constituents in a pasture may play some part in the life of cattle, and indeed, indirectly, in our own lives.

The structure of calciferol is well known; it is based on a skeleton of carbon atoms arranged in this fashion, and it contains, in addition, sundry other carbon atoms and a



good many hydrogen atoms. Recently chemists have been busily engaged on an attempt to find out the cause of cancer and how to cure that disease. They have not yet succeeded in finding a cure, but they have found out a substance that is capable of causing cancer and, curiously enough, this substance is based on a skeleton of carbon atoms like that shown above.

A different set of chemists about the same time was engaged on a research on some singular poisons contained in certain varieties of the toad, and some of these poisons have the same sort of structure as calciferol and the cancer-producing substances.

But the most remarkable discovery of all has been the discovery that the male and female organs of mammals and some other animals contain compounds based on the same carbon skeleton, and that whether an egg or ovum is going to turn into a male or a female seems to depend on the presence of one such compound or another. It will certainly be singular if the difference of sex is found to depend originally on a difference in chemical composition, but this seems to be the fact. In some of the animals not so highly organized as the mammals the sex is by no means a very permanent characteristic; the oyster changes its sex every year, and some other mollusca do the same. It is not outside the bounds of probability to suppose that before long chemists will be able to change the sex of very young chickens, and that these will grow up into healthy birds. But how far it will be possible to make progress in this direction is uncertain. We may know more in the next four or five years, and within the same period the chemists may discover a cure for cancer. At the moment we have to wait and see.

CHAPTER XXIII

FERMENTATION

Fermentation is an old word used to describe the process of converting a sugary liquor into an alcoholic liquid. During the process bubbles of gas are given off and this often indicates the success of the operation. The ancient Egyptians knew how to make wine and beer, and almost every nation has learned these arts; before the Romans came to this country the ancient Britains were accustomed to make a sort of metheglin by fermenting a mixture of water and honey. Fermentation has gradually come to include a very great variety of chemical changes brought about by yeasts, bacteria, or other minute organisms. Cellulose, starch, and sugar are all capable of undergoing fermentation, and they often produce in the process alcohol and carbon dioxide. If damp grass or damp hay is stacked it undergoes a kind of fermentation, and the chemical action that results raises the temperature until it may even cause a fire. Leaves, stalks, and flowers, if moist or wet, usually undergo some sort of fermentation, and wine can be made from elderberries, cowslips, dandelions, and many other sources. Even straw will ferment, and many animal substances will putrefy, and putrefaction and fermentation are very similar processes. The dead leaves in the bottom of a pond ferment or putrefy, not forming much carbon dioxide, but producing the gas methane, or marsh-gas. Indeed, we might claim coal as a product of fermentation. Coal was undoubtedly formed by the putrefaction, by small organisms, of vegetable matter that collected either in an estuarine marsh, or under water. The fossils in coal measures are sometimes land plants and sometimes marine shells or remains of marine fishes, from which we infer that some coals were formed in an estuary with sometimes fresh water, and sometimes salt water.

If we use the word fermentation in the largest sense, as is sometimes the case, we include in this term so great a variety as we have indicated; but there is also a narrower use of the word, restricted to the production by minute organisms of alcohol from a sugary liquid.

The modern conceptions of fermentation are mainly due to that great genius Louis Pasteur, who was trained in physics and chemistry and had no training in biology or medicine, but nevertheless succeeded in finding out for the first time the essential features of fermentation, putrefaction, and infection, and finally in discovering the cure for that dreadful disease hydrophobia. He achieved these most important benefits to mankind by an intense desire to learn the truth and he took infinite pains to find out the essential facts that were necessary to understand the problem, free from any prejudices or traditions that might obscure his judgment. Having made the interesting discovery of the two varieties of the crystals of sodium ammonium tartrate that we have described in Chapter VI, he was led to investigate the action of a very common mould on some racemates and tartrates. These investigations took place in the year 1854 when he was thirty-one years old. Three years later he studied the changes that occur when milk turns sour and forms lactic acid and when sugar solutions are allowed to ferment and form alcohol. He was the first to notice that in the course of this fermentation not only is alcohol formed, but also a little glycerine.

For several centuries there had been a general belief that living creatures could arise from matter that was not living, that if you took a suitable solution and left it exposed to air, in course of time there would be a spontaneous generation of small living organisms. This theory of spontaneous generation was universally accepted in the year 1860, when Pasteur began an investigation of it. He already knew that the spores or seeds of tiny organisms were very widely distributed, and he had a suspicion that a careful study of spontaneous generation might afford a possibility of discovering the origin of a number of prevalent diseases. Among other experiments he prepared a solution that he knew was favourable to the growth of minute living organisms—" infusoria," as he called them. He put some of this solution in a number of flasks with narrow glass necks that could be hermetically sealed by a blowpipe. Some of these flasks were left with an opening into the air; some were half filled with solution and then sealed so that no additional air could enter. Of these latter flasks some were placed for a time in hot water at a temperature sufficient to kill any living germs, and were then removed and stored for a period of two or three years. Wherever he filled or exposed the other flasks, in a town, or in the country, or in the clear and pure air of the high mountains, he found that the solution always began to show signs of change and to produce living organisms. But in no single case was there any sign of this in the flasks that were sealed up and then heated so as to kill the seeds or germs of the small organisms. Pasteur satisfied himself that the transformations of sugar and lactic acid into butyric acid were due to the " infusoria," and he found that a current of air destroyed these " infusoria," or at any rate stopped the fermentation. Pasteur's disbelief in the theory of spontaneous generation led to much argument, but there was no answer to the evidence of his flasks in which a suitable solution had been kept for two or three years, and Pasteur's view that living organisms always proceeded from previous living organisms began slowly to prevail. We think such a belief began slowly to make its way in France about the year 1862 and a little later in other countries, but it took several years before it was commonly accepted by physicians, surgeons, brewers, and the makers of wine. It was Pasteur who first suggested that infectious diseases were caused by small germs, and his study of a few of these diseases, on entirely new lines, enabled him to discover a cure for, or a means of preventing, certain diseases for which no satisfactory treatment was previously known.

In 1863 and 1864 Pasteur was busily engaged in studying the cause of a very widespread trouble that spoilt the wine in many districts of France, and then he was called upon to find a cure for a disease in silkworms that threatened to ruin the silk industry in France. He was successful in both these investigations, and became very well known, and his reputation rose rapidly. He was then asked to find the cause of the difficulty experienced by a brewer who found very frequently that his beer turned sour. Pasteur looked at the small organisms in the fermenting liquor with his microscope, and discovered that those in the good beer were nearly spherical and those in the bad beer were many of them elongated. This method of studying the problems of beer was then quite a new one originated by Pasteur; in the course of about five years he learned the essential facts of the fermentation of wine and beer. Every kind of fermentation is caused by some small organism, and there are thousands of different varieties of these organisms, and each variety will make, under favourable conditions, a particular chemical change resulting in a product with a definite taste, smell, and so forth. It is possible to select a particular kind of yeast and take one or two cells of it, and then place them in a solution of sugar and allow them to grow and multiply. In the course of a week or a fortnight, provided there is enough of a suitable liquid for them to feed upon, the few cells may become a mass weighing several hundredweights. By choosing the right kind of yeast or other organism, you can in this way easily establish a pedigree strain whose properties and habits can be relied upon. One kind of yeast is specially grown for the baking of bread and cakes; one kind is chosen for the brewing of beer at Burton-on-Trent; another kind for brewing lager beer at Copenhagen. For some purposes we suppose a mixture of two or three kinds will be perfectly satisfactory. So also with wines; each vineyard has floating about in the air the spores of a number of wild yeasts, and those specially used in the production of the special wine made there will predominate. So the yeasts that produce Chablis differ from those that produce Beaujolais; the yeasts of Macon differ from those that frequent the vines of Chateau Larose. To grow a wine exactly like Corton, you need a similar soil and climate, similar vines, similar yeasts, and similar methods of fermenting, bottling, and storing.

The fermentation of apple juice to make cider is similar to the fermentation of any other sugary liquid to make alcohol. The ferment causes this change to take place:

$$\underset{\text{glucose.}}{C_6H_{12}O_6} \longrightarrow \underset{\text{alcohol.}}{2C_2H_5OH} + \underset{\text{carbon dioxide.}}{2CO_2}$$

The process is not necessarily quite so simple as this equation, for there may be other sugars present besides glucose, and small quantities of glycerine may be formed in the process, as well as alcoholic compounds that give a distinctive taste or aroma to the fermented liquor.

A different kind of ferment—not a yeast, but a mixture of three species of bacteria—is commonly used for the conversion of alcohol into vinegar, the acid constituent of which is acetic acid. This change takes place in accordance with this equation:

$$\underset{\text{alcohol.}}{C_2H_5OH} + \underset{\text{oxygen.}}{O_2} = \underset{\substack{\text{acetic}\\\text{acid.}}}{CH_3{\cdot}COOH} + \underset{\text{water.}}{H_2O}$$

Acetic acid can be prepared in other ways synthetically, without the aid of any living organism, and in some countries a kind of vinegar is made by adding to water the due proportions of acetic acid and colouring and flavouring matters.

The "vinegar plant" that was used by many of our grandparents to make vinegar at home consisted of a mass of Bacterium xylinum.

Moulds, too, are used in fermentation, and some of these convert starch into sugar and then ferment the sugar into alcohol. There is an important fermentation industry making use of the "amylo" process, and carried on in Belgium, France, Hungary, Italy, and Spain. In this process the substance fermented is starch from maize, rice, potatoes, and manioc, and the ferment used is a mixture of yeast and moulds; the moulds were formerly varieties of amylomyces, hence the name of the process, but now varieties of mucor and rhizopus are used instead.

Maize and malt are both used in fermentation to produce whisky. It is necessary if you wish the ferment to increase rapidly to give it an abundance of food and to have the most favourable temperature. Nitrogen compounds are necessary in the food of the ferment and ammonium salts, now made synthetically in large quantities, form a very good supply of nitrogen for yeast. Phosphorus, potassium, magnesium, and calcium are also needed in small quantities to feed the yeast to the greatest advantage. The Distillers Company makes almost all the bakers' yeast used in this country. In their research laboratories at Epsom a special yeast is kept specially isolated and free from any infection. A mash containing the right proportions of sugar and ammonium salts is made up there, and a large flaskful of this, containing a little of the special yeast, is sent out from the laboratories: this yeast is allowed to grow in the mash, and further food material must be added as the yeast grows. At the end of a week it is divided up and allowed to grow on a commercial scale, and after another week it will be a quantity of about a hundred tons of yeast, which is filtered, pressed into cake, and delivered to the bakers. In this way many tons of atmospheric nitrogen are converted every week first into ammonium salts, and ultimately into the valuable foodstuffs known as proteins, for yeast consists largely of proteins.

In 1910 a French chemist, Fernbach, discovered how to ferment starch so as to produce butyl alcohol, C_4H_9OH, and acetone, $CH_3{\cdot}CO{\cdot}CH_3$ Acetone is used on a large scale as a solvent, and in this country it is made by passing alcohol vapour and steam over a catalyst so as to produce this action:

$$\underset{\text{alcohol.}}{2C_2H_5OH} + H_2O = \underset{\text{acetone.}}{CH_3{\cdot}CO{\cdot}CH_3} + CO_2 + 4H_2$$

A new process was developed by Langwell to produce acetic acid, and other liquids, and combustible gases such as methane, by the fermentation of cellulose; the process is carried out at a temperature of 60° C. (140° F.) and has been brought to an industrial stage.

We have mentioned that Pasteur discovered that in the fermentation of sugar to produce alcohol a small amount of glycerine is made. During the War, when there was a great demand for glycerine, a fermentation process for its manufacture was developed, and it was found that the addition of sodium bisulphite to the mash increased the production of glycerine, but an excess of the bisulphite stopped the activity of the yeast used in the process. For some reason that is not clearly understood, the addition of magnesium salts to the fermentation mash helps the yeast to become more tolerant of the bisulphite. Moreover, if the amount of the bisulphite and magnesium salt is very gradually increased, the yeast seems to get acclimatized to the conditions, and this micro-organism can in this way be gradually trained to alter its procedure, so that instead of producing only traces of glycerine, it will produce a mixture of alcohol and glycerine containing 30 per cent. of glycerine.

There are fermentation processes for the production of lactic acid and citric acid, and there are many other fermentation processes of great importance. The tobacco leaf undergoes a kind of fermentation while it is being cured, and the ripening of cheese is also a type of fermentation. One kind of germ will produce a Stilton cheese, another kind a Gorgonzola, a third a Camembert. Such different kinds of cheeses can now all be made in the same factory if the proper germs are cultivated and due steps are taken to prevent the spores of one kind of germ from infecting a cheese for which they are not intended.

It is not, however, sufficient merely to supply the proper germ in order to obtain a particular variety of cheese. The proper conditions for the growth of the cheese are equally important; the maker must see that the consistency of the milk or cream is exactly right; the temperature must be exactly right; in some cheeses—for instance, Gorgonzola—air must be allowed to enter into the cheese in order to allow the bluish mould to spread and give the cheese the desired appearance and taste.

So far we have considered only the fermentation directly brought about by living germs. But fermentation does not always need the presence of a living organism. It was shown by Buchner in 1897 that by grinding up yeast-cells and then squeezing them out, an extract was obtained that would ferment sugar to alcohol, though not as efficiently as fresh yeast. The substance in the yeast and in the yeast extract that is responsible for the fermentation is an enzyme known as zymase.

In 1901 Wildiers discovered that yeast-cells in a purely artificial medium, composed of a solution of sugar and of various inorganic salts, did not multiply. To ensure growth of the yeast it is necessary to have present some barley or malt or some other natural-grown substance. Wildiers thought that a substance analogous to a vitamin was present in the natural-grown substance, and he called this " bios."

There is other evidence showing that plants, though they will grow for a long period if they are given only pure chemical substances, do not usually attain to perfection and reproduce their species unless there is present in addition something of animal or vegetable origin.

CHAPTER XXIV

HOW THE PLANT GROWS

Animals may be considered from many points of view; the student of evolution, the collector of fossils, the lover of dogs, the keeper of bees, have different problems to interest them. Plants also demand our consideration; we are quite prepared to sit down in Littondale at Whitsuntide and admire the beauty of a mass of Primula farinosa, or to rejoice when we contemplate the autumn foliage or the purple saxifrage; but here we propose also to regard plants as chemical factories, as efficient and interesting as animals, but very different.

Plants and animals vary very much in their complexity; the simplest of both these are small organisms that do not attempt so many chemical operations as the vertebrate animals and the flowering plants. But even the simplest are able to make chemical compounds that are extraordinarily complicated. The difference between the manufacture of chemicals carried on by the sheep or by man, and that carried on by the daffodil or the potato, is the result or the cause of the difference between their habits. Whether we regard it as the cause or the result is a mere question of logic or metaphysics. We regard the chemical processes performed by a living organism as one way of expressing its whole life and structure, and the great differences between the highly developed plants and the highly developed animals are the great differences between their chemical activities. They may, of course, be regarded from other points of view just as usefully.

The mammalian factory has an excellent system of central heating, and the operations can be carried out in winter and summer. The factory is maintained at a very constant temperature, regulated by efficient controls. In normal health the controls work well; in bad health the temperature control may work badly, and a feverish condition may result. The flowering-plant factory has no central heating; it has a number of glass roofs in the shape of transparent cells, and when the sun shines the factory is quite comfortable and the manufacture goes on busily; the operations performed in it require a minimum temperature, and warm weather usually suits them better than cold. Many of the chemical manufactures that are rapidly effected in the plant on a summer day hardly proceed at all during a cold night or the winter months.

The sheep and the weasel, except when they sleep, are active animals always busy seeking the raw materials they require for their operations. They have as raw materials not only the oxygen of the air, but also the substances contained in the foods that they live on. The bear roams the wood, carnivorous, for his prey; the potato and the crocus have to stay where they are rooted, and the only raw materials they can get hold of are those in the air and the soil in their immediate vicinity. We know, of course, that limpets and barnacles lead sedentary lives; but from the window of their house they see a regular stream of traffic, and when they feel so disposed they seize hold of some tempting morsel. Man only—proud, presumptuous man—stores up foodstuffs to supply his regular daily needs all the year round. But many plants have a well-furnished storehouse that they can draw upon when the occasion requires. The starch in the potato tuber, the sugar in the beet, the inulin in the Jerusalem artichoke, are reserves of food. The bulbs of onions, lilies, and snowdrops are storehouses in which starch is kept ready for the use of the plant. Some seeds contain 40 per cent. of their weight in the form of fats and oils, another form of raw materials for the chemical manufacture of the plant that will germinate from them.

The main raw materials needed by the plant are carbon dioxide from the air and water from the soil, but oxygen and nitrogen from the air, and potassium, iron, magnesium, nitrogen, and phosphorus from the soil are also required, and are always available in any soil that will support vegetation.

In the living plant, when the conditions of heat and light are favourable, carbon dioxide and water react to form the carbohydrates, sugars, starch, and cellulose; but the reaction does not take place properly unless the plant has also a due proportion of nitrogen, potassium, and magnesium. The reaction requires also the presence of chlorophyll (see p. 277).

The precise effect of potassium on the plant is not known, but it is supposed that some potassium compound in the juices of the plant helps to absorb from the air the carbon dioxide used in the manufacture of the carbohydrates. There has been a good deal of discussion as to how the carbohydrates are formed, but as yet we do not know the details. It seems reasonable to suppose that there are automatic controls in plants just as there are in animals, and that when enough of a particular substance has been made to satisfy the requirements of the plant, some change in the conditions is brought about that delays the manufacture or alters its character. We may say that the plant can make glucose and maltose and combine these together to make more complex sugars and starches. It would be just as true to say that the carbon and oxygen and hydrogen combine together when the conditions are favourable, and that the compounds so formed make the plant. It is believed that in many plants, when the juices contain enough sugar, the manufacture of this stops and starch and cellulose are made in its place, being stored up ready to be converted into sugar when need arises.

The carbohydrates form the skeleton of the plant, the woody fibres, the hairs, the walls of the cells; they supply the juices of the plant with sugar that can be transported all over the plant and used as raw material for enlarging the structure. The green leaves are the places where the manufacture of the carbohydrates take place; seeds, tubers, and roots the places where they are stored.

The hyacinth bulb lies dormant in the ground during the winter months, with a store of starch sufficient to make a very useful quantity of cellulose for the coming green leaves. When the ground is warm enough and damp enough and other conditions are favourable, a stalk, made partly of cellulose derived from the starch in the bulb, pushes its way into the light. Little rootlets abstract nitrates from the soil and magnesium and other things that are needed, and transfer these to the plant juices. From these juices the plant makes shoots and leaves and all the substances they contain, and when the green leaves appear, the manufacturing operations go on until the summer growth is completed.

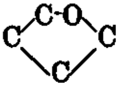
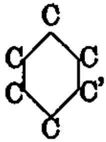
So, too, when seeds are sown in the ground: if the nature of the soil, the temperature, and the other essential conditions are favourable the usual chemical changes will take place, and from the air in the soil and the soil itself raw materials will be absorbed into the seed, so that cellulose, starch, and proteins will be made and the seed will sprout. One essential condition is that the seed is alive, that it contains the enzymes in a living state necessary for the maintenance of the chemical actions. Life implies much more than mere catalytic action stimulating chemical combination; life in the case of a plant implies that the various chemical combinations shall take place at such times and in such parts of the plant as are duly ordained and inherited. If it is part of the nature of the seed to lie dormant in the soil, for the first three days or three weeks it will lie dormant; if it is part of the nature of the plant to put forward its new green leaves in April, that tendency will prevail, and we know quite well that if the nature of the plant is to make a leaf half-an-inch long, when that length is reached the work will stop in that particular area and a new leaf will be begun in some other part. This directing force is part of life, and we know very little about it; small variations in the directing force exist, and may sometimes be encouraged by careful selection and breeding, but the main features persist from one generation to another, and there are shell-fish existing to-day that differ in no essential detail from those that existed hundreds of millions of years ago.

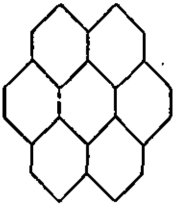
Living plants and animals have very little or no choice about their growth. The seed does not know that it is time to put forth its tender root—it knows no more about this than the baby knows of the growth of its fingers; given good health, the fingers will grow as fingers do; we know a little of the chemical changes that cause the growth; we know practically nothing about the nature of the inherited control, and can only watch its effects.

The primary function of the plant, its main purpose in life, is to produce seeds so that the race may be perpetuated. This is nature's plan. To this end the plant makes cellulose and rears its leafy stalk as high as possible; to this end it advertises its existence by scents and glaring colours, attracting insects to fertilize the flowers. Or it may dispense with the assistance of insects and save any expenditure on advertising, and rely on the wind to fertilize the flowers. The plant must have a sufficient height not only to allow free access of wind and an appearance attractive to insects, but also to enable the green leaves to receive enough sunshine, and to permit the seeds to be scattered far enough away from the parent plant to enjoy an independent existence. It would be futile for a perennial plant that normally grows about a foot high to deposit a few hundred seeds in a little heap round the base of its own stalk. Many plants make use of ingenious devices to ensure that their seeds are well distributed. The ash and the sycamore have winged seeds that are carried away by the wind, and when the right times comes there are chemical changes in the little stalk so that the wind can detach the seeds from the tree. The willow-herb and the cotton have hairy seeds that also are blown about; so have the thistle and the dandelion. Other seeds are prickly, like those of the geums; these are distributed by sheep and other animals. Some seeds are brightly coloured and sweet tasting, so that birds shall carry them off to distant places; to make this device a success the plant prepares at the right time special colouring matters in special structures. The mountain-ash berries delight our eyes; they are not intended to please us, but the missel-thrushes. The colouring matters of plants are the result of complicated chemical processes, so interesting that we shall devote a special chapter to their description.

All the raw materials that are needed by plants are available in the atmosphere and ordinary soils; the plants have the structure and the composition that they have because during a period of many millions of years they have unconsciously made chemical experiments with the atoms and molecules that lay at hand, and the successful experimenters have flourished from one generation to another.

It has already been mentioned that sundry proteins are found in plants. We can only conjecture how they are made, but these proteins are essential to the life of the plant, and every living cell contains some amount of protein, so that the making of protein must precede in strict logic the making of sugar or starch, although both these manufactures take place simultaneously so long as the plant continues to grow. It seems as if the plant must first make the amino-acids from which the proteins are made, but this sequence of events is a mere assumption, and the evidence for it is not conclusive. Actually when the living plant has a suitable environment, and a suitable temperature, the proteins are formed, and when the amount of these is too large for one cell, the cell splits into two complete cells, and the process continues.

We have explained some of the elementary facts about the way plants make sugar, and starch, and cellulose; but there is another substance that plays an important part in the growth of the large plants with a woody structure. Wood contains a considerable proportion of lignin, an aggregate of rings with six carbon atoms, rings with four carbon atoms and one oxygen atom, and sundry OH and CH_3 groups. Probably there are many varieties of lignin, and the constitution of none of these is known, although several ingenious guesses have been made. Professor Bone, who has devoted many years of study to this subject, is satisfied that lignin is an important constituent of peat, brown coals, and lignites, or at least that it is the parent substance from which these fuels have been formed. It is reasonable to conclude, as he does, that such fuels in the course of millions of years lose some of their oxygen, and that the rings of  are rearranged, after the loss of the oxygen atom, as benzenoid rings , or perhaps, more truly, rings of six carbon atoms. The oldest and most advanced coals, the bituminous coals, and in particular the anthracites, contain less oxygen and less hydrogen than the brown coals and lignites, and it seems that much of the carbon—in some cases nearly all—consists of benzenoid carbon rings, carbon atoms united together in such a structure as this:



When lignites, brown coals, bituminous coals, and anthracite are treated with oxidising agents under suitable conditions, various benzene oxidation products are formed, indicating that some of the original benzene structure of the lignin has persisted until the end.

It should not be supposed that all these benzene rings existed in the living plants from which the coal was ultimately made. Some were formed during the putrefaction, and the subsequent changes that took place when, over a long course of years, oxygen and hydrogen left the plant residues, and the carbon atoms were left to rearrange themselves as seemed most convenient. Carbon atoms have a hexagonal tendency, as we may see in graphite.

CHAPTER XXV

THE CHEMICALS NEEDED FOR PLANT LIFE

SOME moulds, bacteria, and other simple organisms are capable of living on a very simple food in which very few chemical elements are concerned. Yeast as we have shown on p. 254 (Chapter XXIII), demands oxygen, hydrogen, nitrogen, carbon, and small amounts of a few more elements, but the more highly developed plants that we cultivate in our gardens and fields require a greater variety of elements.

The green colouring-matter, chlorophyll, the formula of which is given on p. 277, is a compound of magnesium, and unless the soil contains a small percentage of magnesium compounds, no green plant can grow. Fortunately, magnesium is widely spread; the sea contains magnesium compounds, and sea spray is easily blown about by the wind; dolomite and other rocks also contain magnesium. The soil must also contain potassium compounds; as these are found in the sea, in many volcanic rocks, in wood, and other common substances, the soil is seldom devoid of potassium. Then calcium is essential, but calcium is found in limestone, chalk, shells, and bones; most soils contain calcium. Other elements necessary for plant life are iron, aluminium, manganese, copper, titanium, boron, silicon, sulphur, chlorine, fluorine, and iodine. Sometimes a crop is stunted or diseased in one field or a part of a field, and an analysis of the soil is made; some element—manganese or fluorine, for instance—is found to be missing, and when a suitable compound is added to the soil, the crop recovers its health and flourishes (see Plate VII, p. 244).

In a state of nature when the plant dies it rots on the ground, and although some of the carbon, oxygen, hydrogen, and nitrogen may escape into the air as gaseous compounds, all the metallic elements—the silicon, the fluorine, and many others—will remain in the decomposing vegetable matter, and will be available for a future crop. The same elements are used again, year after year, or generation after generation, and never leave the land in which they begin their career.

It is different in cultivated land: the corn is gathered and taken somewhere else to be threshed, the straw goes to one place, the flour to another. In this way the chemical elements of the soil are being slowly and steadily abstracted from the country and taken to the towns. Gradually the soil becomes impoverished, and the chemical elements that are becoming deficient must be restored in the shape of artificial fertilizers. The elements that are taken away from the fields most commonly and most quickly are nitrogen, phosphorus, potassium, and calcium. The calcium is restored in the shape of lime, nitrogen as sulphate of ammonia, phosphorus as basic slag or bone-meal, potassium as wood ashes or as a part of a mixed fertilizer.

All green plants are capable of taking carbon dioxide from the air, and water from the soil; it is unnecessary to restore carbon, oxygen, or hydrogen; the restoration of nitrogen to the soil is rather a complicated process, and an appreciation of it will enable us to understand the nature of soil and the scores of chemical operations carried on by minute organisms in the top few inches of our soil. It is not necessary for a plant to be large in order to be an efficient manufacturer of chemicals. Minute, almost invisible, moulds can perform very complicated chemical operations, and so can bacteria that are quite invisible to the human eye.

Now. we ought not to regard the soil as a mere mixture of particles of sand, clay, chalk, and pieces of dead leaves and other vegetation. The soil—or at any rate the top two or three inches of it—has a teeming population more varied and more crowded than the population of the surface, using the word population to include all kinds of living organisms. If the surface has its human beings, cattle, dogs, rabbits, trees, herbs, and moss, the soil has immense quantities of bacteria, algæ (allied to the simplest sea-weeds), amœbæ, fungi, and other very simple forms of life, to say nothing of worms of all sizes, from earthworms, down to microscopic ones, insects, and so on. Now, these organisms are present in quantity, four or five tons of bacteria to the acre, perhaps, and perhaps a ton or two of fungi to the acre, a hundred-weight of algæ, and a hundred-weight of odds and ends to the acre. We are not attempting to give exact figures, for these vary very much; we are only indicating the sort of scale in which these organisms occur in the top few inches of a fertile soil. They are busily engaged in feeding on decaying vegetable matter and in feeding on each other. When conditions are favourable, one group flourishes exceedingly and grows in numbers very rapidly, only in time to become an easy prey to some other organism. These organisms require for their food some of the same substances as do the oats, potatoes, and roses; they store up nitrogen in their cells; they die and leave the nitrogen, perhaps in a form useful to the higher plants, perhaps in a form the higher plants cannot cope with.

When we consider the digging and hoeing of the soil, watering it, the effect of the sun's heat, the effect of artificial fertilizers, and lying fallow, we must consider mainly the changes brought about in the prosperity and numbers of the various groups of the soil life. Some may die out, and those that are accustomed to feed on them will starve; some other groups of organisms will find an opportunity for abundant increase; they may be organisms that help the higher plants to live; they may be injurious to the higher life.

During the last fifty years, and especially during the last thirty years, the soil and its inhabitants have been very carefully studied, and we know now a good deal about the part played by the different kinds of bacteria. It has been known for centuries that it is good for the land to grow a crop of beans, lucerne, or clover after two or three crops of corn or cabbage. The fertility of the soil is somehow restored. About fifty years ago the explanation was discovered. Very many of the leguminous plants (the beans, peas, clovers, lucernes, and other plants that have their seeds in a row in a pod) commonly have small lumps or nodules on their roots, and these nodules are colonies of thousands or millions of bacteria that take nitrogen from the air and oxidize it, so that it can combine with some of the mineral constituents in the soil to form nitrates (see Plate VIII); they make more nitrates than they need for their own use, and even more than the leguminous plants need for their use; there is a certain surplus quantity available, if desired, for a crop of oats or mustard for the following year.

The leguminous plant and the bacteria work together on a co-operative system, for their mutual benefit, as the nations of the world ought to do. The bacteria supply the plant with nitrates; the plant supplies the bacteria with carbohydrates, and normally they get on very well together, but if the plant is starved or kept in the dark, so that it has no spare carbohydrates, the partnership breaks up, and the bacteria, instead of working partly for the benefit of the plant, become parasitic on it. The bacteria commonly live in their nodule, but there comes a time in their life when they grow a hair, or sort of tail, and by wriggling this they move through the soil. They can travel at the rate of about an inch in twenty-hour hours, seeking, we may suppose, for the root of some other clover or bean.

This taking up of nitrogen from the air by the nodules of leguminous plants is of great economic importance, not merely a laboratory experiment; it is done on an enormous scale. But there are other kinds of bacteria that are able to take nitrogen from the air. There are also bacteria that can make nitrates from decomposing vegetable matter, or from nitrites, or from ammonia. Nitrites are substances like the nitrates, but they contain less oxygen. The sulphate of ammonia that is added to our fields is, no doubt, mostly converted into nitrates before it is used by the crops. Most plants take all their nitrogen in the form of nitrates, but grass seems to be able to take some nitrogen in the form of ammonia. The decaying matter of plants is partially converted by bacteria into nitrites; these are converted into nitrates, and these enter into the plant to form proteins and other compounds. There is a continuous cycle of conversion of proteins into nitrates by bacteria and a reconversion of the nitrates into proteins by the plants. And the proteins in plants help the animals that feed on them to make their own proteins.

Man is now taking a hand in the nitrogen cycle. The synthetic manufacture of ammonia and nitric acid from the atmosphere adds each year a large amount of nitrogen, which is ultimately converted into proteins, and forms a permanent addition to the food supply of the world. About 100,000 tons of nitrogen are taken from the air each year by the chemical factories of Imperial Chemical Industries at Billingham (see Plate VIII). This nitrogen, except an insignificant fraction, is all converted into ammonia compounds or nitrates and used to fertilize the ground. It is then converted into proteins by green plants, by bacteria, and other organisms, and this huge tonnage of proteins becomes the food supply of man, or perhaps some herbivorous animal that finally is eaten by man. But this artificial manufacture of nitrates is itself only an imitation of nature, for the electric discharges in the air are continually converting nitrogen into oxides of nitrogen, and these are dissolved in the rain, and so washed into the soil. Thousands of tons of nitrous and nitric acid are in this way added to the soil every rainy day.

It must not be supposed that we have alluded to all the operations, chemical or otherwise, of the algæ, fungi, bacteria, and other living organisms of the soil. They decompose all the dead vegetable and animal tissues in or on the soil; they help to spread about the products of decomposition, and the larger animals—for instance, earthworms—do a great deal to keep the soil well aerated. The effect of the lower organisms on the nutrition of the higher plants is a mere accident or incident in the lives of the lower organisms; their main business is feeding on decaying tissues and on each other, a constant struggle for existence continually varying with the temperature of the soil, the presence of rain, the falling of dead leaves, and such other phenomena.

The living organisms of the soil have in some instances a more specific action than we have indicated. Certain fungi grow on the roots of plants in a manner that assists the plants to grow. What the relation is exactly is not quite clear, but many orchid seeds will not germinate unless a special sort of fungus is present in the soil; so, too, the heath, Calluna, requires a special fungus for its due development; some species of Pinus will not grow in soil that is not infected or infested with the special fungus needed. There is a sort of co-operation that exists between the heaths and the fungi that grow with them, and this co-operation persists throughout the life of the heath. The cranberry requires also the companionship of a fungus, but the relationship has not been worked out in detail.

The restoration of nitrogen to gardens and arable land is not so complicated a business as the restoration of nitrogen to pastures. Perhaps we should speak rather more generally, and refer to the improvement of pastures by the addition of nitrogenous fertilizers. Nitrogenous fertilizers, of which sulphate of ammonia is the most popular, for some unknown reason promote the growth of grasses more than they promote the growth of weeds, so that the grasses eventually overpower the weeds; the fertilizers also stimulate the production of the colouring matters, chlorophyll and carotene, in the grass and in such herbs as the buttercup. A dressing of sulphate of ammonia to pasture-land that needs such treatment provides not only food for more sheep, but it also enables the cows to give us milk that has more vitamins in it. The exact changes in the herbage, caused by adding nitrogen fertilizers to pasture, depend partly on when the fertilizer is added, and also when the sheep or other grazing animals are turned on to the land. Some grasses respond more quickly than others to the application of nitrogen, and they will quickly grow and be eaten by the grazing animals, so that later in the summer or autumn they may be crowded out by other grasses or by clover or some other herbage. The whole character of pasture land may be altered in two or three years by changes in the times of adding fertilizer and in the times of grazing.

Let us see how controlled grazing can alter the composition as we have stated. If sheep are allowed to graze early in the spring—in March and April—and are taken off the pastures after that, they eat up the grasses which grow somewhat earlier than the clovers, and the clovers flourish at the expense of the grasses. After two years of this, what was once a grass field is now predominantly clover. Similarly, by grazing later in the summer, the clovers are punished, and grasses once more predominate. By adopting the best system, the fields can be made to support more head of cattle or sheep and provide more hay over a number of years than if they are grazed heavily every year and gradually become more impoverished.

In the Middle Ages most of the pastures in this country were unenclosed, and no fertilizer was added to increase their fertility, except sometimes a little marl—a limey kind of earth. In the winter the sheep and cattle had very little grass to eat, and they were glad to get hold of the leaves of evergreen trees or any other kind of food; they were very badly fed for five or six months in the year, and they grew to a small size.

Adam Smith in his *Wealth of Nations*, in referring to the report of the Select Committee on the Cultivation of Waste Land in 1795, stated: "In the reign of Queen Anne, in 1710, when half the stock of the Kingdom were fed on unenclosed commons, the cattle and sheep sold at Smithfield market weighed on an average as follows: Beeves, 370 lbs; calves, 50 lbs.; sheep, 28 lbs. Now (1795–1800), it may be stated, Beeves, 800 lbs., calves, 148 lbs., sheep, 80 lbs., and lambs, 50 lbs. The increase is principally, if not solely, to be attributed to the improvements which have been effected within the last sixty years, and the feeding of our young stock in good enclosed pastures instead of wastes and commons." At the present time beeves weighing 1800 lbs. and sheep weighing 135 lbs. are not exceptional, and it is quite easy to breed and fatten heavier animals than these. It is recorded (see p. 5) that when Cavendish, probably about the end of the eighteenth century, suggested that a leg of mutton should be prepared for a party of five or six, his housekeeper told him that one leg of mutton would not suffice. Legs of mutton have grown since then, and one such joint will satisfy half-a-dozen scientific men and leave some over. We are learning, though slowly, how to provide more beef and mutton, more eggs and butter, and all of a better quality, and we are learning how to store and to transport these without spoiling them. Much of this is due to the labours of the chemist.

One of the most recent developments in connexion with the improvement of our meadows and pastures is due to the enterprise of Imperial Chemical Industries, who have experimented on the grazing and the fertilization of grasslands for some years, and during the last three or four years have been investigating the possibility of drying grass so as to preserve a larger proportion of the proteins contained in the grass.

The grass that grows in the early part of the year—April and May, for instance—is very rich in proteins and is a valuable food for horses, cows, and sheep. If it is cut and dried in an oven a very considerable proportion of the proteins and the vitamins in the grass is preserved. It is desirable not to wait until the grass is very long and old; it is better to cut it twice in the early part of the year and once in the late autumn. In this way it is possible to obtain from an acre of ground a greater amount of protein in dried grass than in any other form of crop. The drying of grass has already been practised on a considerable scale, and appears to be commercially attractive. The dried grass is a very much richer crop than ordinary hay. By the time the grass is ready to cut as hay it has already got past its prime so far as proteins and vitamins are concerned, and the process of drying the hay in the open, especially in a damp summer, does not preserve the proteins and vitamins so well as a quick drying that takes only a few hours. If the drying of grass in an oven becomes a common practice, it will be possible to give animals during the winter as good food as they now obtain, perhaps better, relying only on dried grass, and saving the present expense of oil-cake and such foodstuffs. Assuming that this interesting experiment turns out to be as good as it seems, it will tend towards a change in the practice of treating our grassland. There will be a tendency not to preserve the present distinction between pasture-land and meadow-land, but to mow the grassland and graze it in alternate years.

CHAPTER XXVI

THE COLOURS OF LEAVES AND FLOWERS

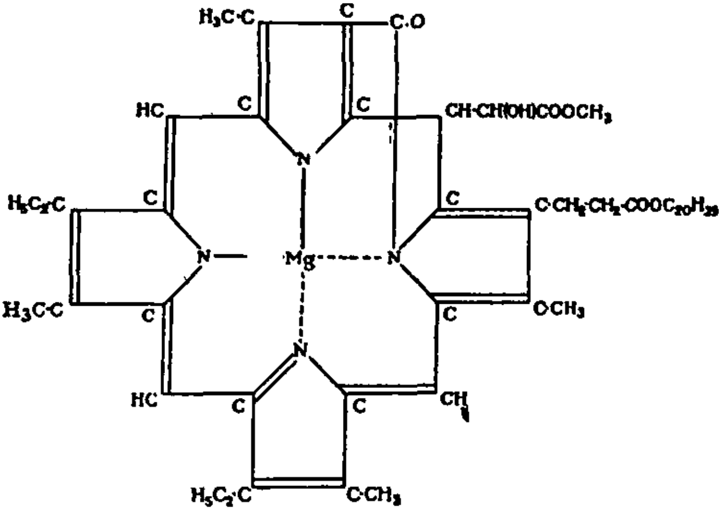
The delight that we experience when we look at beautiful plants and flowers is not entirely due to the beauty of their colour. This is but a part—an essential part, it is true—of the cause of our pleasure. To this part may often be added the graceful forms of the leaves and flowers, and the marvellous ingenuity with which the various parts are made so as to carry out the operations for which they are designed. There may also be that infinite variety and constant change of light and colour that is so great a part of the charm of the ever-changing sea. When we sit down to enjoy a landscape of meadows and pastures, with elm trees in the hedgerows and perhaps a group of dark pines or spruces, we find a wonderful variety of green shades, depending on very many circumstances, and as we only sit down for this purpose when our minds are free from work and worry, we are able to withdraw our minds into their happiness, as the poet said, and annihilate all that's made into a green thought in a green shade. To these various causes of our pleasure another must be added—the pleasure of recollection, just as this contributes to our happiness when we read again a favourite book. Some of us when we see the pink flowers of *Primula farinosa* are reminded of Littondale; the daffodils remind us of Kew Gardens; the bright colours of the autumn foliage remind us of Nova Scotia and of Virginia. A bright patch of heather brings back to our minds many pleasant holidays spent near Midhurst, near Ingleborough, in the Sma' Glen, at Balmacara, and many other places.

To the human eye colours are not those absolute things that we might suppose them to be. Every green ought to have its own wave-length and we might think that any particular shade of green would therefore look the same. But this is not so to our eyes A green of a particular wave-length does not seem to us the same when it is placed next to a blue as it does when it is next to a yellow. The human eye is a very delicate and sensitive instrument, but it is subject to influences quite apart from wave-lengths. Our senses react upon each other; our sense of smell is associated with our sense of taste; our senses of smell and of taste are, in some way that is not easily explained, associated with our sense of sight. It is a waste of money to offer a fine cigar, or a fine wine, to some one in the dark.

There is no need to fear that our pleasure will be diminished if we know a little of the nature of the colouring matters that stimulate our emotions in this manner. A little such knowledge may even add to our enjoyment. The colouring matters of plants were not, so we suppose, designed for our delectation, any more than the mountains, and rivers, and the gorgeous colours of the sunset were so designed. The plant pigments are in some cases designed to attract insects, or, if they were not so designed, they have become necessary to the fertilization of the plants and their continuance from generation to generation. Other pigments are reserves of raw materials required by the plants for their daily life. Others are probably waste materials for which the plant has no further use.

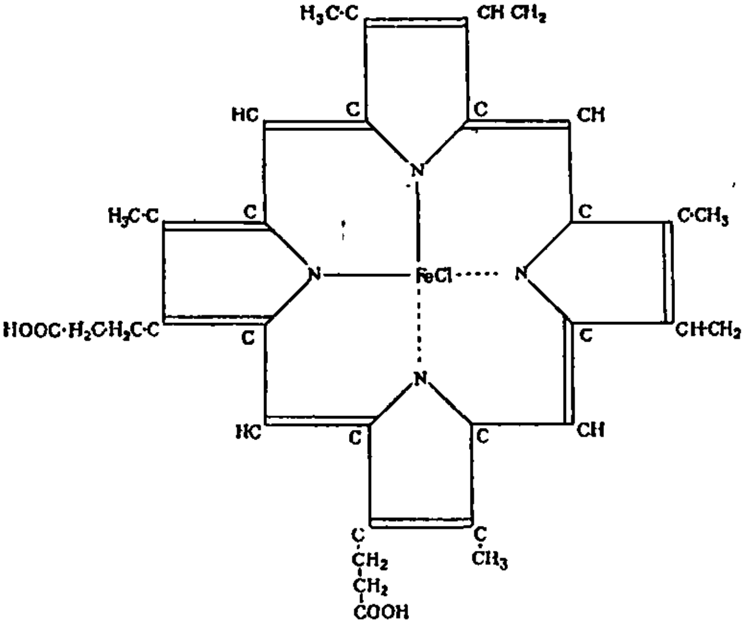
In the spring, before most of the flowers are in bloom, the prevailing colour is green, but some of the early flowers are yellow—the crocus, the daffodil, and the buttercup, for instance.

The green colour of our common herbs and flowers is mainly due to the pigment chlorophyll, a complicated substance, that enables the plant during the daytime to absorb carbon dioxide from the air. Chlorophyll resembles the hæmoglobin of the blood in this respect: it easily absorbs the required constituent of the air, and easily releases this to the cells that need it, and the gaseous molecules that are not required by the plant are in due course given up. Chlorophyll acts as a catalyst; it is continually acquiring and parting, but light is certainly necessary to its power of acquiring, and so we find that plants grown in the dark—as they will for a while—have no green colour. Rootlets and underground stalks have



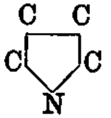
a-Chlorophyll.

no green in them, as we know from the celery on our table. Moreover, if a green plant is kept in the dark, it will lose its green colour. It is easy to blanch endive or dandelion leaves by placing a flat stone over them to keep out the light. And chlorophyll resembles hæmoglobin, or rather the non-protein or pigment part of it, in another respect: they are constructed of very similar elements, arranged in a very similar manner, though hæmoglobin has atoms of iron in it, and in chlorophyll these are replaced by magnesium. Above we give the formulæ for one variety of chlorophyll—for there are at least two—and for hæmin, the only part of hæmoglobin of which the formula is known:



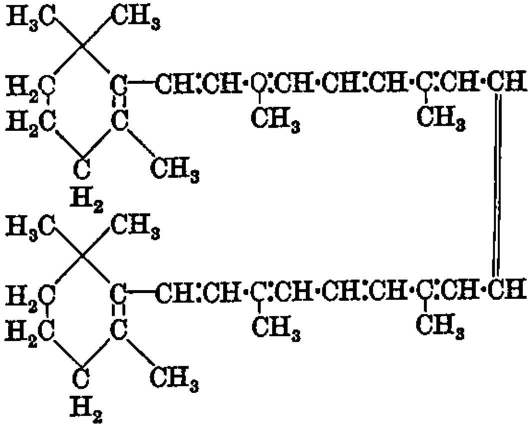
Hæmin.

It will be noticed that both chlorophyll and hæmin are built up on a structure of four rings of this type:



—pyrrol rings they are called. The details of these two formulæ are not yet universally agreed by the chemists who have worked at them, but the main principles are agreed.

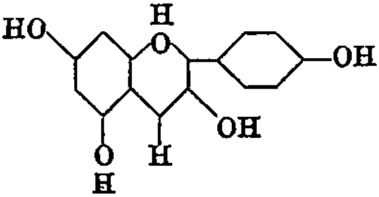
Another extremely common colouring matter in plants is carotene, a complex hydrocarbon, that is found mixed with chlorophyll in the green leaves of grass, nettle, and very many other plants. It forms the yellow colour of the flowers of the buttercup and the daffodil, and gives the reddish-orange colour to the root of the carrot; when it is separated and purified it has a deep red colour. There are two or three different varieties of carotene, of which that called β-carotene is the most abundant. It sometimes occurs in nature mixed with α-carotene and sometimes alone. This is the formula of β-carotene:



We have already discussed the importance of carotene as the substance from which vitamin A is made.

A colouring matter that is very similar to carotene is lycopene—the reddish colour of the tomato fruit and the capsicum. It has a long chain of CH groups like that of carotene, but differs from the carotenes in the rings at the two ends of the chain.

When man uses colours for decorative or attractive purposes he has an enormous range of pigments to choose from. There are red and brown oxides of iron, vegetable dyes like indigo, prussian blue (a compound of iron and cyanogen, CN), a silicate (ultramarine), vermilion (a compound of mercury), chrome yellow (a chromate of lead), white lead, zinc white, titanium white, and other metallic compounds, and in addition some eight or nine hundred dyes or pigments prepared from coal-tar, including every shade of colour. The flowering plants have almost an infinite range of colour, but, with the exception of the greens and yellows, they are almost all founded upon one substance combined with one or two kinds of sugar. These colours are glucosides, called by the general name of anthocyans. There are two sugars made use of by plants for combination with the third substance, and these two sugars are glucose and rhamnose. The other constituent of the pigment is pelargonidin or some substance derived from it by substituting an OH group for an H atom in one or two places, or by substituting a CH_3 group for an H atom in one or two other places. By making these simple changes and by varying the sugar in the compound, a whole range of colours is obtained—scarlets, crimsons, violets, purples, blues, and blacks.

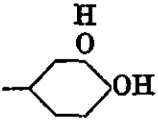


Pelargonidin.

The structure of this remarkable substance, pelargonidin, is given above.

It is not found in plants by itself, but always in combination with *glucose or rhamnose*, and in this combination it provides the colour of the scarlet geranium (pelargonium), red aster, scarlet salvia, and scarlet gladiolus.

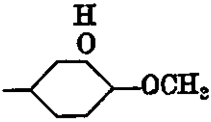
The hexagon at the right hand of the formula is a ring of six carbon atoms, to which are attached H atoms like those in the benzene ring. Change one of the hydrogens in this into an OH group thus:



Cyanidin.

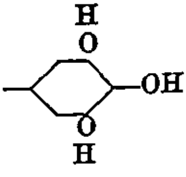
and we get a purple series of glucosides, compounds of cyanidin with glucose or rhamnose. These form the colouring matters of many dahlias, asters, purple poppies, cherry fruits, cranberries, chrysanthemums, roses, sloes, and elderberries.

If in this hexagon a CH_3 group is substituted for a hydrogen atom thus:



we get a purple found in the pæony.

If, instead of two OH groups in the hexagon, there are three OH groups thus:



Delphinidin.

we get a new substance, delphinidin, which when combined with glucose gives us the blue colour of the delphinium. Another glucoside of delphinidin gives us the deep blue of the pansy.

Other glucosides closely related to those we have described give us the colouring matter of grapes, bilberries, and hollyhocks. These interesting substances have been studied for many years by numerous workers, including Keeble and E. F. Armstrong, and Willstätter and Everest. Many of them have been artificially prepared by Prof. R. Robinson of Oxford and Mrs. Robinson.

It seems that in all cases the formation of these colouring matters by the plant requires the presence of an enzyme.

Many plants, as sweet williams and some varieties of primula, have flowers in which certain parts are coloured and the other parts are white. It has been shown by Keeble and Armstrong that unless the enzyme is present in the proper place, the colour is not formed. In some flowers the white parts are wanting in pigment because the enzyme is not present; in other flowers all the ingredients of the pigment are present all over the petals, and so is the necessary enzyme, but some additional substance is present in spots or a band that prevents the colour from being formed or released, and a variegated petal is the result.

The formation of the colour is not merely a chemical problem; we must consider also the inherited characteristics of the plant. If it has inherited the property of forming in July white petals with a crimson border, then the formation of the crimson will, as a general rule, be *confined to that special place and that special time.* The plant has no more choice in the matter than we have in the shape of our finger-nails or the colour of our hair. Nothing, or hardly anything, is known about the method employed by nature to ensure these inherited characteristics, but every gardener knows quite well that at the ordained time the petals will be formed and coloured in the accustomed manner. It is true that very occasionally there is a small departure from what is expected, and very likely the seeds of such a plant will in due course produce plants that show the same departure.

The experiments that proved the constitution of the anthocyans and enabled chemists to prepare artificially so many of them are full of interest to chemists, and make a most interesting story. But it is not an easy one to tell except to chemists, for it involves more long and strange words and more elaborate diagrams than most people could tolerate. It is, however, a quite remarkable achievement that chemists can connect benzene rings together in almost every way in which they occur in nature and in very many other ways, and can replace any particular hydrogen atom by an OH group or a CH_3 group, so as to obtain the score or more of varieties of these anthocyans that they are interested in. Horace says somewhere that nothing is too difficult for mortals; perhaps he is right, but it is beyond the power of the authors of this book to explain these details in the space available and in easily intelligible language.

CHAPTER XXVII

INHERITANCE

One of the most extraordinary features of living things is their power of gradually growing to resemble their parents. A tiny cell, consisting mainly of thousands of molecules of the proteins and thousands of molecules of water, all vaguely grouped together under the name protoplasm, enclosed in a cell-wall containing thousands of molecules of cellulose, has inherent in it the power of developing predestined complications almost beyond our belief. If this tiny cell is an ovum of a delphinium, and has been duly fertilized, it will become a ripe seed containing starch and the faculty of sending out a root and two simple pointed leaves that will be green if there is a suitable soil, light, temperature, moisture, and so on. The plant will grow; its first simple leaves will die away; new and larger leaves will appear, not simple, like the first ones, but deeply indented in accordance with a very complicated plan, not only one of the many thousands of possible leaf-plans, but one of the hundreds of varieties of such a possible plan. There is one plan that enables you to recognize at once a delphinium leaf, but there are many varieties of this, and your seedling will have, in nine hundred and ninety-nine cases out of a thousand, the variety of leaf characteristic of the mother plant. In due course the tiny cell we are considering will have grown into a sturdy plant perhaps six or seven feet high, with one particular manner of growth, quite different from a primula, or a teazle, or a rose, a rush, or a willow. This manner of growth is inherent in the original cell, in the aggregate or molecules that we have referred to. What chemical compounds determine this heredity we do not know, and possibly we never shall know; but we are not acquainted with any kind of substance that is not composed of molecules or some other aggregations of atoms, or at any rate of the groups of nuclei and electrons that make up atoms. We are therefore driven to conclude that some particular collection of groups of nuclei and electrons will, in the presence perhaps of other special collections, absorb water, and carbonic acid, and nitrates, and other substances, and compel these to grow into juices and cells. These will gradually form stems that will divide into two stems, or will form at fairly regular intervals two branch stems, with a pair of leaves at each interval, all according to the hereditary nature of the plant.

This inherited complexity goes through every feature of the plant. If we consider a seedling derived from a uniform strain of delphiniums, we may find that the seedling will resemble its parents, and grow up to bear beautiful and elaborate flowers with sepals and petals all arranged in perfect order, with most definite shapes that distinguish them from the countless different shapes of the corresponding parts of buttercups, columbines, lupins, wallflowers, campanulas, and so on.

The delphinium has a great, almost an infinite variety of colours, from light mauve and light blue to deep blue or purplish blue. One variety has five sepals, two of which are a light mauve, one is partly light mauve and partly light blue, the other two are light blue; two of the sepals join to form a sort of spur, such as we find in the ordinary nasturtium (tropæolum) or columbine. In this variety there are four, or sometimes more, small petals, two of which are mauve and two of which are partly yellow and partly mauve.

Another very usual variety of delphinium has five dark purplish-blue sepals, two of which are joined to help form a spur; it has four, or sometimes more, small petals, two of which are dark brown and two of which are partly a light brown and partly yellow.

There are many other varieties to be found in our gardens —light blue delphiniums, dark blue delphiniums, delphiniums with nearly black small petals, and others with white petals, and there are hybrids or crosses of these showing the signs of their mixed parentage. These hybrids are not unfertile, like the mule, described by Gibbon as having no pride of ancestry and no hope of posterity. The hybrid delphiniums, like the hybrids of many other plants, go on from year to year and generation to generation producing single cells containing molecules or other aggregations containing not merely the possibility, but the certainty of producing almost all the characteristics of their parents. The difference between the colours of the delphinium depends, so far as we can observe, solely on the inherited power of adding to a standard molecule a methyl group, CH_3, here, or there, or in some other position, or making a similar trifling alteration to the chemical constitution of the colouring matter of the flower.

This inherited power of effecting a particular chemical reaction is characteristic of all plants and animals, but is more easily observed in the larger and more highly developed plants and animals. Shellfish have the power of absorbing various items from the sea in which they live; most of them absorb calcium carbonate, which they build into elaborate and beautiful shapes; some absorb small quantities of arsenic, or copper, or manganese, or nickel from the sea-water and store their favourite metallic drug in their livers; some absorb a particular constituent and make from it a pigment with which to colour their shells in accordance with a definite and often complicated scheme.

The different species of nautilus inherit their own complicated patterns, dividing one compartment of the shell from another; different kinds of mollusca had their own colour patterns of their shells so far back as the times of the *carboniferous limestone*; the oysters that absorb arsenic from the sea have offspring that absorb arsenic from the sea. The swallow-tail butterfly has patches of black and yellow and other pigments in the very same places on its wings as its grandfather and grandmother had and very many much earlier ancestors.

So, too, with man; he starts as one tiny cell, fated, in a manner from which there is no escape, like a character in a Greek tragedy, to undergo a remarkably complicated course of development: the cell becomes an embryo of a fish-like, gill-possessing type, and then produces mammalian characteristics, until finally it has the inevitable two hands with a thumb and four fingers on each hand, a nail of a particular shape and colour on each thumb and finger, and all the other details that characterized the parent or the grand-parent of the individual in question. Had the grandfather and father blue eyes, or curly hair, or a large lip, or an aquiline nose, or a long foot, or a quick temper, or a tendency to gout or baldness, or short sight, or a swarthy complexion, that characteristic will very likely persist for many generations, though not necessarily in every generation; curiously enough, the tendency to resemble a parent advances throughout life; if a son resembles his father, the resemblance will often be more striking when the son is fifty than when he is five-and-twenty.

We can conceive of nothing that will account for these similarities and these almost certain inheritances except minute differences between the compositions of the various ingredients that make up the original cell that forms the connecting link between one generation and the next.

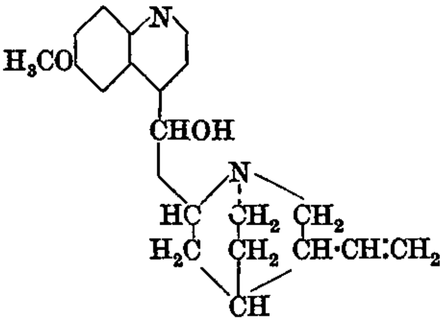
We cannot conjecture or imagine what these differences consist of, but there they are in the original cell, and the substances in them are fated to produce five-fingered star-fishes, or six-legged beetles, or eight-petalled dryas, or blue delphiniums, or sweet-scented wood-ruff, or scarlet pimpernels for ever, or until some catastrophe cuts short the line. We can identify the colouring matter, or the scent in the adult; we cannot identify in the embryo the agent that will ultimately produce it. But we are certain it is there.

We are not to assume that nature is quite fixed and unchanging; we know the contrary. Sometimes a " sport " appears in a plant or an animal, and by careful selection and breeding a new variety can be developed. The *Lotus corniculatus*—the common birds' foot trefoil—is of two varieties that cannot be distinguished from each other except chemically; the one produces a small quantity of a glucoside that yields prussic acid, the other does not. If we were to collect a few plants with an unusually high percentage of this glucoside and breed from these plants, no doubt in time we should have a strain yielding a higher percentage than is now obtainable. Careful selection and breeding have enabled us to grow beets with a high proportion of sugar, tobacco with a high proportion of nicotine, indigo with a high proportion of colouring matter, and yeast with an unusual power of performing some special chemical action of fermentation.

In the case of domestic animals and cultivated plants, we can do much to increase their size by giving them abundance of good food and favourable conditions, and by selection and careful propagation we can rear strains, immune to some diseases, or having special characteristics that are desired by the community; we have done much to improve the breeds of horses, cattle, sheep, pigeons, poultry, wheat, barley, potatoes, beans, cabbages, grapes, and apples; we have done very little with man; he is an obstinate being with ideas of his own; he is not much bigger or stronger or more sensible than he was a few hundred or even a few thousand years ago; our modern poets do not write better poetry than Vergil did, nearly two thousand years ago, nor than Homer did, nearly three thousand years ago. We have our wireless, our motor-cars, and our gramophones; we do not greatly surpass the pyramids, the temples, and the theatres of the ancients; are our modern plays so much superior to those of Æschylus and Sophocles? Are our modern writers, excellent as they are, better than Pascal, Dante, and Plato?

One rather singular illustration of the property, inherent in cells, of reproducing the type of plant or animal concerned, is furnished by many gnats, flies, and similar common insects. The eggs of these are destined to produce larvæ with eyes, digestive systems, nervous systems, six legs, and a number of other structures; the larva turns into a pupa, corresponding to the inactive chrysalis of the butterfly, and finally emerges as a perfect insect with eyes, mouth, proboscis, digestive, nervous, breathing, and reproductive systems, six legs, two wings, and a whole host of other complicated structures The legs of the adult gnat are not developed from the legs of the larva, but are separately formed, so that in the pupa of the gnat you may find at the same time the relics of six larval legs and the beginnings of six adult legs; the pupal stage is a state of revolution sometimes leading to anarchy; in some of the two-winged insects the creature retains many of its old structures while the new ones are being slowly constructed; in others there is a far greater destruction of the original organization before the new organization gets going. In the common house-fly we have an advanced state of anarchy in the pupal stage; all the internal structure of the creature seems to disappear; it has no vestiges of limbs, no digestive system, it eats nothing and does not breathe; it is reduced to a state of mush enclosed in a hard skin, but this mush gradually splits up into groups, begins to form an alimentary canal, legs, wings, eyes, and so on, and in the fulness of time the perfect insect emerges ready to enter our houses, eat our scraps of food, and enjoy its life in its own way. In this instance the inherited power of producing six legs is not exhausted by the first successful effort; having achieved this, the animal destroys all its structure and seems to mix up the debris of its old parts into a chaotic semi-liquid mass in which the capacity of producing six legs still persists. In some ways this is a more surprising thing than our own capacity of producing two sets of natural teeth.

A rather odd example of the inheritance of the power of making special chemical compounds is furnished by the large class of the alkaloids. The alkaloids are complicated compounds made by a few plants; they all contain a ring of carbon atoms and a nitrogen atom with sundry groups attached to the members of the plant. The alkaloids are often very bitter to taste; some are very poisonous; some of great value in medicine. They are usually colourless crystalline compounds, and on the whole they are of value to man; what value they are to the plant no one knows. Most plants get on very well without them; the few plants that produce alkaloids belong to a few orders of the flowering plants, and we commonly find that a few different species of the same genus, if they produce alkaloids at all, produce very similar alkaloids. The valuable drugs digitaline, morphine, strychnine, and quinine are alkaloids; nicotine is another alkaloid; opium is a mixture of alkaloids, and so is the drug known as nux vomica. It is possible that the amino-acids may in certain cases assist in forming alkaloids, instead of the proteins which seem to be the obvious substances needed by the plant. Perhaps the bitter taste of the alkaloid preserved the plant from being eaten by sheep and rabbits, perhaps the plants with more alkaloid stood a better chance of survival than those with less alkaloid, but the grasses and daisies get on very well without any alkaloid at all. The fact is that by selection and cultivation you may gradually produce a foxglove with more digitaline and cinchona plants with more quinine, and these plants are cultivated on a considerable scale for the sake of their alkaloids. The quinine alkaloids are of great value as a cure for malaria, and are commonly taken as a cure for a cold; but whether they are of great value as a cure for a cold, it is hard to say. Perhaps it is sufficient to believe that quinine will cure a cold. This is the formula for quinine itself:



There are other alkaloids also found in the same plant of rather similar properties and rather similar structures. The opium, strychnine, and other alkaloids have entirely different structures. Perhaps some day we may learn something about the reason for the existence of alkaloids in plants.

We have now come to the end of our task; we have perhaps made it a little more difficult than we need have done, for we might have confined our attention exclusively to the very simple substances and the very simple problems. On the other hand, we wished to face the facts as they are, and to endeavour to explain familiar things and everyday occurrences, even though they are complicated.

The chemistry of water and all solutions is not easy, the burning of a lump of coal is not to be represented by a simple equation; all solid bodies—or almost all—are as complicated as we have stated them to be, and we only delude ourselves if we suppose them to be otherwise The chapters about the structure of the atom are difficult for the same reason that a description of the mechanism of a motor-car is difficult. So, too, the complexity of life and all its ways is such that no simple account of it can be written. We have only attempted to describe a few isolated facts about living organisms, and have not made the description as full as is possible. In our imperfect way we have tried to explain a few aspects, and our readers and ourselves know that we have only touched very lightly indeed on an insignificant proportion of the topics that occur to one's mind. There are very many excellent books available to those who wish to increase their knowledge of chemistry, matter, and life.

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