FROM ALCHEMY TO CHEMISTRY

JOHN READ

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TO

THE MANY COLLABORATORS AND OTHER FRIENDS
'THAT HAVE TOIL'D, AND WROUGHT, AND THOUGHT WITH ME'
IN DIVERS COUNTRIES AND CLIMES

The systems which confront the intelligence remain basically unchanged through the ages, although they assume different forms . . . There is nothing so disastrous in science as the arrogant dogmatism which despises the past and admires nothing but the present.

HOEFER

Moult plaist a Dieu procession,
S'elle est faicte en devotion

NICOLAS FLAMEL (1413)

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PREFACE

JAMES CLERK MAXWELL, one of the greatest figures in physical science of the nineteenth century, once wrote: 'In Science, it is when we take some interest in the great discoverers and their lives that it becomes endurable, and only when we begin to trace the development of ideas that it becomes fascinating.' Between two and three hundred years earlier, the poet, John Donne, had written that in order for a mystery to have a universal significance it must be made comprehensible to ordinary mortals.

These two pronouncements have been kept constantly in mind throughout the writing of the present book. There seems to be no reason why alchemy and alchemy's daughter, chemistry, should remain a mystery to ordinary mortals. It ought to be within the capacity of the educated adolescent and adult of normal intelligence, no less than within that of the student and teacher of chemistry, to follow the course of the dominating ideas, discoveries, and theories which have determined the progress of this great branch of science from the earliest times down to the present day: provided always that he does not become entangled in a web of specialised and technical detail.

The layman is too often repelled from taking an intelligent interest in chemistry by the mere sight of serried rows of chemical equations and pages of cryptic formulae and symbols. These are certainly necessary in text-books and monographs, which are bound to enter into fine detail and to use the complicated symbolic representations of modern chemical shorthand; but these formidable representations are unnecessary in a broad survey of the origin and development of chemical science. Intelligible expositions of science are a crying need of the present age; for never has it been so important as today for the ordinary adolescent, and the ordinary man and woman, to know how science arose, how it developed, and what it is doing; also to understand the general implications of the new knowledge and the possibilities and powers that it brings.

Chemistry, in particular, is capable, when suitably presented, of making a strong appeal to the intelligence and the imagination; for, as the following pages are intended to show, it is the most romantic of all the branches of science; and in its variegated history, stretching back through unnumbered generations of alchemists into an indefinite past, its present votaries have (if they but knew) a richly human and humanistic heritage.

The present book continues a central theme of three earlier volumes, *Prelude to Chemistry* (1936), *The Alchemist in Life, Literature and Art* (1947), and *Humour and Humanism in Chemistry* (1947),[1] in the last of which it is claimed that historical science 'if approached befittingly, may reasonably take rank beside the so-called humanities as a broadly educative, cultural, and humanising influence; and that the specialised outlook which is becoming increasingly bound up with the trend of scientific research may be alleviated by the cultivation of an interest in the broad humanistic aspects of science.'

The same note was struck in the writer's Presidential Address to the Chemistry Section of the British Association in 1948, with the corollary that 'there should be no sense of antagonism between arts and science, either in the schools or out of them. These studies are complementary.' In the admirable words of a *Times* leader of 11 August 1956: 'scientists . . . tend to look back now less on a succession of revolutions in knowledge, each making a break with the past, than on a course of progressive approximation to a truth never finally attainable. The whole past has become again relevant; and thereby a new bridge may be built

[1] See the list of books of reference on p. xvi and the corresponding footnotes in this book.

across the schism in culture which is so often deplored . . . it is through scientific more than through humanist eyes that our grandchildren are most likely to view the world. But they will not understand their world picture—so now the scientists themselves agree—unless they know something of the long historic effort by which it has been drawn, unless, that is, they are able to conceive of the sciences themselves under the aspect of the time process in which humanists are accustomed to think.'

It may be added that realism has been sought for the present narrative by frequently reporting ideas, happenings, and characteristics of leading personalities in the language of the day; moreover, most of the illustrations have been reproduced from original sources.

Finally, although this book ranges from ancient Egypt and still more remote times to the present day, from the conceptions of primitive religions to those of the electronic theory of matter, and from methane to macromolecular substances, it contains only a handful of chemical formulae, and withal one solitary chemical equation. That equation needs no apology, for it ought to be known of all men:

$$2H_2+O_2=2H_2O.$$

THE UNIVERSITY,
ST. ANDREWS, SCOTLAND
April, 1957

REFERENCES AND ACKNOWLEDGMENTS

IN writing this book, I have referred repeatedly to some of my earlier ones, and in particular to Nos. 1 to 6 below, of which Nos. 1 and 3 are out of print:

1. *Prelude to Chemistry*, Bell, London, 1936, 1939; Macmillan, New York, 1937.
2. *Humour and Humanism in Chemistry*, Bell, London, 1947.
3. *The Alchemist in Life, Literature and Art*, Nelson, Edinburgh and London, 1947.

These three books form a trilogy.

4. *A Text-Book of Organic Chemistry*, Bell, London (latest edn.).
5. *An Introduction to Organic Chemistry*, Bell, London (latest edn.).
6. *A Direct Entry to Organic Chemistry*, Methuen, London (latest edn.). (Awarded the Cortina-European Prize, 1949.)

Among other works of which particular use has been made are the following:

7. Chaucer's *Canterbury Tales*, edited by A. Burrell (1908), Everyman's Library, London and New York.
8. *The Autobiography and Personal Diary of Dr. Simon Forman* (from MSS. in the Ashmolean Museum, Oxford), edited by J. O. Halliwell, London, 1849.
9. Ben Jonson's *The Alchemist*, The King's Library edition, London, 1903.
10. Justus von Liebig's *Familiar Letters in Chemistry*, 4th edn., London, 1859.

The present work contains occasional footnote references to some of the above publications, and from these books it is usually possible to find original sources. Some interesting information about Paracelsus was obtained from the study by Basilio de Telepnef, published at St. Gallen in 1945; and some of A. E. Waite's translations from the original Latin have been used, particularly as given in *Prelude to Chemistry*.

The original sources of most of the illustrations are given in the

list of illustrations, to be found in the forefront of this book. Acknowledgments are contained in that list and are also hereby made for kind permission to publish the following reproductions: the portrait of Priestley (Fig. 34) in the National Portrait Gallery, London, by permission of the Trustees; and the two diagrams of Lavoisier's Experiment (Figs. 36 and 37), from Dr. J. B. Conant's Book, *On Understanding Science* (1947), by permission of the Yale University Press.

Blocks for Figs. 9, 18, and 19 have been kindly lent by Messrs. Thomas Nelson and Sons, Edinburgh (from Reference 3, above); for Fig. 27 by the Aberdeen University Press (from my study, *William Davidson of Aberdeen*, 1951); and for Fig. 31 by Messrs. Jackson, Son and Company, Publishers to the University of Glasgow (from a further study, *Joseph Black, M.D., the Teacher and Man*, 1950). I express my thanks to the lenders of these blocks and also to Mr. Robert Morris, University of St. Andrews, for his valuable help in preparing photographic material.

It should be added that shortly before his death, in 1952, Professor Tadeusz Estreicher, of Cracow, one of Poland's most cultured and distinguished men of science, provided the photograph from which Fig. 23 has been reproduced, together with some information about Sendivogius.

J. R.

I · BEGINNINGS

Concerning the Nature of Things

CHEMISTRY, in a rudimentary form, must have been coeval with civilisation. At a very early stage in the evolution of man as an observant and thinking being he must have formed some kind of misty idea respecting the nature of the material world around him. He planted his feet upon the solid earth, waded through the running streams, and breasted the strong winds of his environment. Also he discovered how to produce fire. So he became conscious of earth, air, fire and water, and also of many different kinds of matter, or 'stuff,' with which he came into contact. He discovered many uses to which they could be put, either in their native state or after treating them in various ways. He found that fire, which at first he had regarded with superstitious dread, could be brought under control and used with advantage by reason of certain changes that it could bring about in the nature of material things, as well as acting as an agreeable source of warmth.

Man has been described as a thinking animal. He is also possessed of an insatiable curiosity. In the intervals of his struggle for existence, which consisted largely in this primitive state in securing food, shelter, and protection from the many dangers that threatened him, he brought his rudimentary reasoning powers to bear upon the character of everyday things and phenomena. Then he sought to bring his observations into some kind of order and to establish a general framework into which he could fit them. In the fullness of time his dim ideas blossomed into what we may regard as primitive theories.

Probably the earliest integration of this kind which is of interest in the remote ancestry of science arose from a primitive mode of human thinking based upon a distinction between pairs of opposites: this has been called the 'Doctrine of the Two Contraries.' Thus it is significant that in the first chapter of the Book of Genesis chaos is depicted as being reduced to order by the separation of opposites, of day from night, of light from darkness, and of the waters from the land. Moreover, the universe of the ancient religion of Mesopotamia was conceived as being under the control of Baal, the Father God, and Astaroth, the Mother Goddess. Baal, the Sun-god, was a hot, active, light, immaterial and positive principle; Astaroth, the Moon-goddess, was cold, passive, heavy, material and negative. Osiris and Isis took similar positions in the cosmology and religion of ancient Egypt.

The Doctrine of the Two Contraries found a much later and more elaborate expression in the earliest fundamental theory of physical science, known usually as the 'Theory of the Four Elements.' Although often ascribed to the great Greek philosopher Aristotle (*c.* 350 B.C.), this theory goes back much farther in time: its essentials had been recognised in Egypt and India more than a thousand years earlier. In the Orient, the related Chinese conception of the Five Elements (*Wu-hsing*), based also upon the Doctrine of the Two Contraries (*Yin-Yang*), likewise claims a great antiquity.

Aristotle's theory rested upon the supposed existence of four elementary properties or qualities. These formed two pairs of opposites: hot and cold, wet and dry. When combined pairwise, as represented in the appended diagram (Fig. 1), they gave rise to the four fundamental simple bodies, or elements: earth, air, fire and water. All kinds of matter were held to be composed of these four elements, associated in different proportions. Further, according to Aristotle, the four elements were also incorporated with a *prima materia*: this had no material existence until it became allied with 'form,' after which it could enable one element to pass into another, by a process of transmutation.

Hovering behind these four elements was a shadowy and ill-defined fifth. Aristotle called it ether, the element of the stars; the neo-Platonists called it Logos, otherwise the Word, God, or Reason; and among the medieval philosophers it was known as the *quinta essencia*, fifth being, or quintessence, sometime confused in alchemy with the Philosopher's Stone.

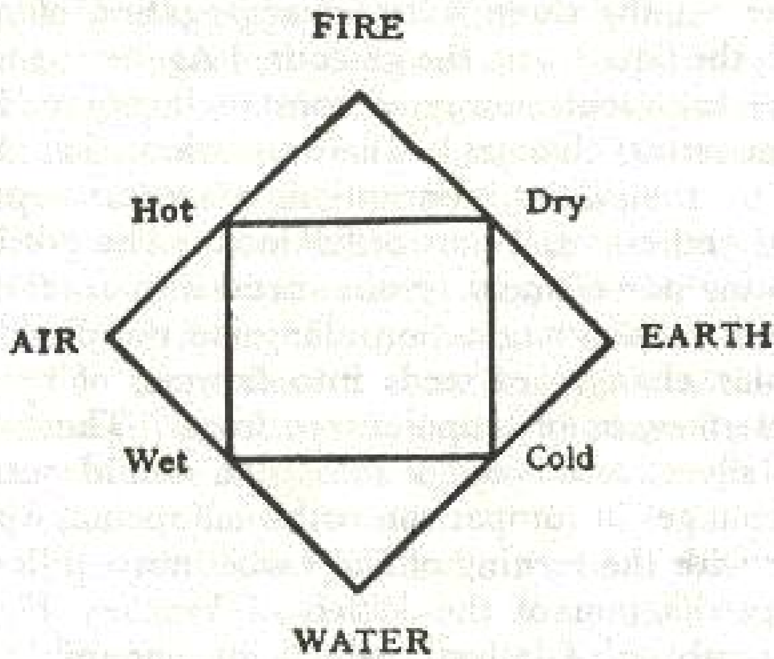


Fig. 1. The Four Qualities and Four Elements

The Aristotelian theory dominated scientific thought until the time of Robert Boyle in the middle of the seventeenth century. Its implication of the possibility of changing, or transmuting, one element into another was particularly important. As an example of this conception, it appeared that water, the cold-wet element, could be transmuted by the application of heat into air, the hot-wet element, through the displacement of the cold quality by the hot one. In modern terms, of course, this process of vaporisation is considered as a purely physical one. Solid water (ice), liquid water, and gaseous or vaporised water (steam) are different physical forms of the same substance, and there is no question of transmutation of one kind of matter into another being concerned in interconversions of these three forms.

It would be unjustifiable, in the light of present knowledge, to dismiss the theory of the Four Elements as ill-conceived or useless. Clearly this theory summarised in a compact form the result of long ages of observation and thought. In one sense, the 'elements' Earth, Water and Air represent the three states of aggregation of matter—the solid, the liquid, and the gaseous. Again, the 'element' Fire may represent energy, a constant agent in bringing about material changes. Transmutation, in turn, belonged to the wider conception of metamorphosis, a universal and essential part of folklore. The possibility of transmuting one element or one metal into another would be ranged in the imagination alongside the observed and spectacular changes of seeds into flowers, of caterpillars into butterflies, or of tadpoles into frogs. The turning of tin into silver, or of copper into gold, would seem to be trifling changes in comparison with such metamorphoses as these, or with the turning of Lot's wife into a pillar of salt, or the petrifaction of the Witch of Wookey Hole by a 'lerned wight of Glaston,' when—in one of 'Mendip's sunless caves'—

> The ghastly hag he sprinkled o'er;
> When lo! where stood a hag before,
> Now stood a ghastly stone.

The philosophers of ancient Greece were much concerned with the problem of the ultimate constitution of matter, upon which they held divided opinions. There is little doubt that their ideas were inherited to a large extent from the earlier civilisations of Egypt, Syria and Asia Minor. According to Aristotle (*c.* 350 B.C.), matter is continuous and therefore capable of infinite subdivision; but Epicurus (*c.* 300 B.C.), elaborating the pre-Aristotelian views of Democritus of Abdera (*c.* 400 B.C.) and Leucippus (sixth century B.C.), held it to have a grained or discontinuous structure, consisting of atoms of the same primordial material which differed in their size, shape and form. The Roman poet Lucretius, in the first century B.C., expounded this conception of an atomistic structure of matter with great fervour and eloquence in his famous work, *De Rerum Natura* ('Concerning the Nature of Things').

Since the Greek philosophers had little inclination for experiment, and reached their conclusions by processes of abstract thought, their ideas were merely speculative and remained unresolved for more than two thousand years. Nevertheless, this early interest in the nature of the 'stuff' of which the material world around us is composed was sustained throughout succeeding ages, and led eventually to a rudimentary form of experimental science known as alchemy. For more than a thousand years alchemy remained essentially static, until, during the seventeenth and eighteenth centuries of our era it blossomed slowly into the modern science of chemistry.

Modern chemistry deals with the study of the 'stuff' of the material universe. It is obvious at a glance that 'stuff' of many different kinds lies around us, or, in other words, that matter is heterogeneous and not homogeneous or of uniform composition. A lump of granite, for example, is distinct in its appearance and also in its properties from a pool of sea-water.

Chemistry goes beyond superficial observation of this kind, and shows that granite and sea-water themselves are heterogeneous materials. One of the leading tasks of chemistry is to devise processes for separating from such mixed materials their various homogeneous constituents. Thus, when the heterogeneous material, sea-water, is distilled it yields a homogeneous liquid material known as water. This distinctive kind of matter is called a 'substance.' The residual sea-salt is still heterogeneous. It consists of a mixture of several other substances, among them being common salt. These solid substances can be separated from each other by using further processes which take advantage of their different properties. Such separative processes play so important a part in chemistry that this science used to be known in German as *Die Scheidekunst*, that is, 'the art of separating.'

Chemistry does not stop at this point. It proceeds far beyond the preparation of pure individual substances from naturally occurring materials. Each individual substance has to be characterised by a study of its properties. Also chemistry is concerned with the composition of each distinct substance and with the possible ways of breaking it down into simpler substances and of building it up from other substances.

The kind of information thus acquired is all of a 'qualitative' nature, concerned with the kinds of constituents; but of equal importance is the 'quantitative' aspect, which depends upon weight and measurement and takes cognisance of quantity or proportion.

All such studies are fundamental; but they constitute only a fraction of the functions of modern chemistry. Historically, they did not begin to come into effective action until the second half of the eighteenth century.

Concerning the Application of Things

In the pre-history of man, knowledge must have been acquired slowly and laboriously, by trial and error, of the different properties of the many materials that came to his hand. The manipulation of things and their application to everyday uses, particularly in the provision of food, fuel, clothing and shelter, brought a familiarity with their properties and paved the way for later speculations concerning their fundamental nature.

Such a sequence ran through the whole history of chemistry until the present age. The rule-of-thumb applications of things, bringing a growing acquaintance with their properties, led to an increasing knowledge of their intimate structure. In other words, application preceded theory. In recent times the close knowledge now gained of the fine structure of matter has tended to reverse this sequence; so that theory may now often dictate methods of adapting natural materials, or even of elaborating purely artificial ones designed for specific purposes.

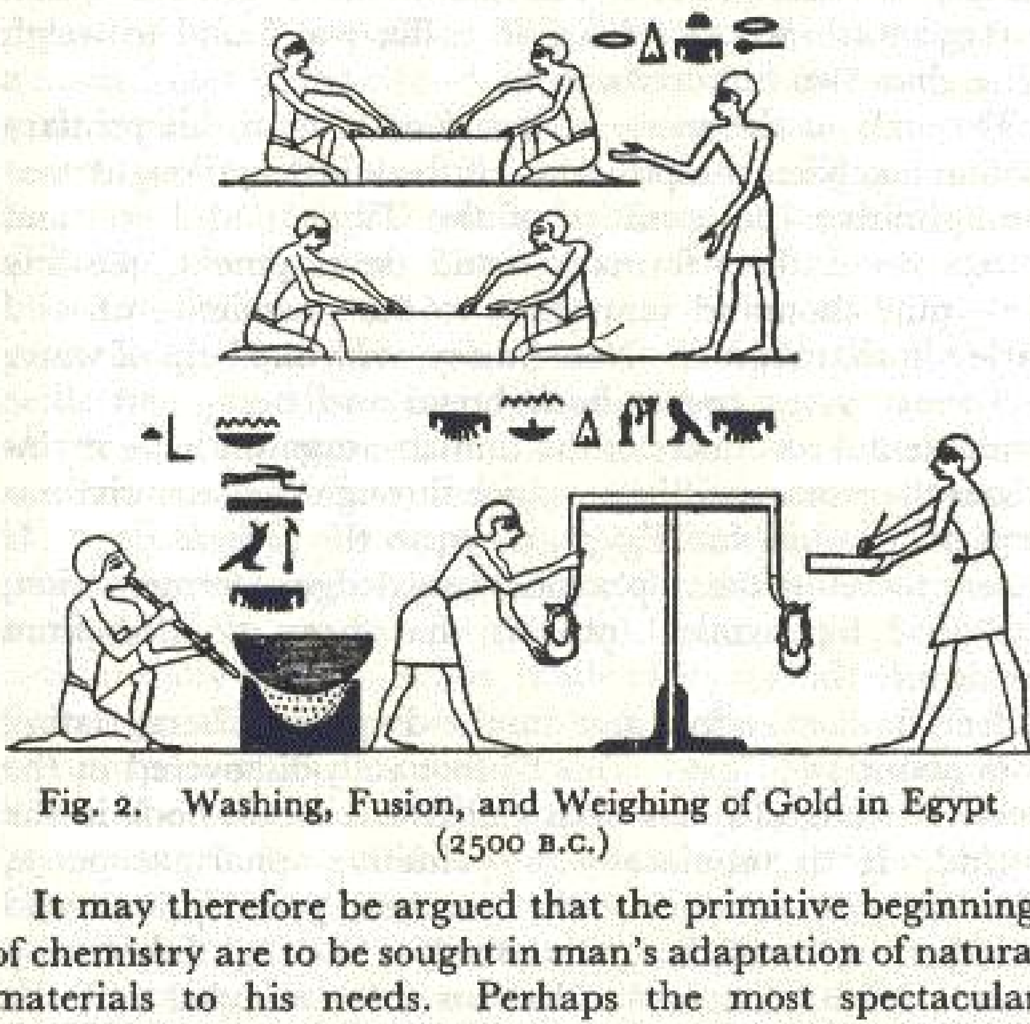


Fig. 2. Washing, Fusion, and Weighing of Gold in Egypt (2500 B.C.)

It may therefore be argued that the primitive beginnings of chemistry are to be sought in man's adaptation of natural materials to his needs. Perhaps the most spectacular, although by no means the most common, of these materials is gold. This gleaming yellow metal, malleable and untarnishable, lent itself readily to use in the decorative arts of early man. In the Euphrates valley there were expert workers in gold so long ago as 3500 B.C., and the washing, fusion, and weighing of gold were depicted in drawings on the walls of Egyptian tombs a thousand years later (Fig. 2). This beautiful metal, which remains unaffected by any ordinary agency, has always held a high place in man's esteem. There is indeed little doubt that the development of alchemy was largely bound up with attempts to solve the problem of the occurrence of gold in the earth's crust and to produce it artificially. The oldest map in existence is one of a gold-mining region in ancient Egypt; it dates from about the time of Tutankhamûn (*c.* 1350 B.C.), whose solid gold coffin was found to weigh more than two hundredweight.

Throughout the many civilisations of man, his primary motive has been the provision of food. It is thought that the primitive communities of the Tigris and Euphrates valleys owed their formation and development, possibly some nine thousand years ago, to the prevalence of wild barley in that region. Now barley, with the help of water and yeast, gives rise to both bread and beer; and these fundamental sustainers of the human organism have maintained their primeval importance through the later civilisations of Babylon and Egypt, down to the present day. It is clear therefore that a practical knowledge of fermentation, a typical biochemical process, has been applied from prehistoric times.

Beer finds mention also in the Papyrus Ebers, dating from about 1550 B.C. This 68-foot roll, discovered in the Theban necropolis, has been called 'the oldest book in the world.' It is essentially a primitive pharmacopoeia, containing more than eight hundred prescriptions and remedies. One of these, described as 'a delightful remedy against death,' consisted of half an onion mingled with the froth of beer. The Papyrus states also that garments may be protected from the depredations of mice by smearing them (i.e. the garments) with cat's fat. Mention is made of many mineral ingredients, such as stibnite, sulphur, soda, lead, common salt and saltpetre. The Papyrus Ebers provides the earliest written example of the close connection between chemistry and medicine, an association that was destined to become of the first importance to chemistry some three thousand years later, in the so-called period of iatrochemistry. Thus, in the search for remedies to cure human ills and to prolong life can be traced another far-reaching root of chemistry.

Among such remedies, plant products took a prominent place. There was a great demand for the spices, incenses and perfumes of southern Asia and its adjacent islands for these and other purposes. This demand constituted indeed a main factor in the rise of traffic and commerce among the early civilisations. Trade flowed along the caravan routes extending from China, India and Arabia to Egypt and the Black Sea. Later, Phoenicia, by virtue of its geographical situation, became a distributive centre of commerce between Orient and Occident; and Sidon and Tyre, in particular, acquired much wealth and fame thereby.

The use of medicinal remedies has been closely associated all down the ages with attention also to the outward appearance of the human body, yet it is somewhat surprising to find that the application of beautifying materials, which we now call cosmetics, stretches back into a remote antiquity. In the British Museum, for example, there is a substantially built toilet box, made of wood and mounted on four legs, which may be described as the ancient Theban counterpart of the modern 'vanity bag.' It belonged to Tutu, the wife of a scribe named Ani, who lived about 1400 B.C. It was used as a receptacle for various aids to beauty, including unguent vases of terra-cotta and alabaster, and a double stibium tube with pencils for applying the contained powder and medicinal paste. Stibium, a name given to various black powders and specifically to native antimony sulphide, was in common use among the lovely ladies of long ago for darkening their eyebrows and eyelashes and also as a protective paint in hot and dusty weather.

It was some five hundred years after the days of Tutu that the Sidonian princess, Jezebel, 'painted her face, tired her head, and looked out at a window,' upon the rapid approach of Jehu the son of Nimshi. Her action has been partly misrepresented by unduly severe critics of later generations, seeing that she 'put her eyes in painting' [a more accurate translation] at least partly as a routine protective measure against dust and insects.

The Assyrians had a word *guhlu*, meaning 'eye-paint,' and this was later rendered into Arabic as *kuhl*. The 'kohl pots,' or 'kohl tubes' used as containers for these black stibium powders were often exquisitely designed and ornamented. Among specimens still extant is one in faience inscribed with the name of Tutankhamûn's queen. Others, still older, are delicately carved in ivory with designs modelled on papyrus-buds and stems of lilies. Later, among the Romans, the perfume bottles, scent boxes and other containers for cosmetics, were characterised by their delicate workmanship and elegant designs.

In many ways the ancient civilisations had a keen sense of beauty. This they applied in modelling, shaping and decorating the materials which they found to suit their purposes. Constant practice of this kind led them to gain an ever-increasing knowledge of the properties and adaptabilities of the things they handled. They acquired a practical knowledge of a surprising range of processes, such as brewing, soapmaking, glassmaking and dyeing, which are now included in the operations of chemical technology.

Indigo-dyed wrappings of mummies found in the tombs of ancient Egypt have kept their colour to the present day: they testify to the skill of the dyers of those far-off days. Most of the ancient dyes were of plant origin. There is little doubt, for example, that both indigo (from the indigo plant) and alizarin (from madder) found application in dyeing Joseph's coat of many colours. The most costly dye known to the ancient world was, however, of animal origin. This was the famous Tyrian Purple, the imperial colour, the use of which was denied to ordinary mortals. It was extracted with meticulous care from the glands of certain shellfish (*Murex*) found in the waters of the Eastern Mediterranean. There were large factories for this purpose at Tyre and Sidon, and others are known to have existed at Athens and Pompeii.

It was of this Purple of the Ancients that Browning wrote:

> Who has not heard how Tyrian shells
> Enclosed the blue, that dye of dyes,
> Whereof one drop worked miracles,
> And coloured like Astarte's eyes
> Raw silk the merchant sells?

It is one thing to discover a coloured substance; but its attachment, in a fast or permanent condition, to a fabric is a different and often difficult matter. That the ancient dyers had attained a complete mastery of the art of dyeing with Tyrian Purple is clear from the assertion of Lucretius in *De Rerum Natura*: 'The purple dye of the shellfish so unites with the body of wool alone, that it cannot in any case be severed, not were you to take pains to undo what is done with Neptune's wave, not if the whole sea were willed to wash it out with all its waters.'

II · THE EMERGENCE OF ALCHEMY

Rise and Spread of Alchemy

WHEN, where, and how alchemy arose is impossible to say; but the name points to Egyptian and Arab sources, since *Khem* was the ancient name of Egypt and *al* is the Arabic definite article. For this reason, Egypt, or Khem, the country of dark soil, the Biblical Land of Ham, has often been held to have given birth to alchemy, the 'art of the dark country.' It is certain that the ancient Egyptians were skilled in a great variety of arts, such as dyeing, glass-tinting, enamelling and metallurgy, which gave them some rudimentary knowledge of chemistry.

Sometimes, again, it has been supposed that alchemy arose farther to the east, in Chaldea, or even in China. The Chaldeans were notable astrologers, and they associated the sun, moon and planets not only with human destinies, but also with the known metals. Still farther east, in ancient China, alchemical ideas found a place in the comprehensive religious and philosophical system of Taoism. Much later, in the second century A.D., Wei Po-Yang, who has been called 'the father of Chinese alchemy,' wrote the first Chinese treatise devoted entirely to alchemy, wherein he described the preparation of the 'pill of immortality,' the Chinese equivalent of the Elixir of Life of Occidental alchemy.

The ultimate origin of alchemy is thus a vexed question; but on the evidence available it seems to have sprung up among the skilled metallurgists and metal-workers of the Middle East, possibly in Mesopotamia, whence it spread westwards to Egypt and Greece, and eastwards along the caravan routes to India and China.

In this tangled web of hypothetical alchemical origins it is known that as far back as the sixth century B.C., there was a great intermingling of the natural philosophy of Persia, Syria, and Greece in the ancient and long-forgotten city of Harran, in Syria. The Sabian craftsmen of Harran were skilled in metallurgy and in many other operations calling for a knowledge of the materials of primitive chemistry. A later co-ordination of such knowledge and ideas took place in Hellenistic Egypt, where, in the early centuries of the Christian era, originated the earliest written treatises on alchemy: these were influenced greatly by neo-Pythagorean and neo-Platonist philosophy.

With the rise of Muslim power in the seventh century A.D., and the consequent absorption of Alexandria and other centres of Greek culture, the growing corpus of alchemical knowledge and ideas was transmitted to Islam, through Syria and Persia. This corpus of alchemy was of a dual nature. On the one hand, it was essentially practical and allied closely with the arts, crafts, and medicine; on the other, it was an indistinct aggregation of vague mysticism and cryptic expression. These two main aspects of alchemy persisted throughout the Middle Ages.

So it came about that until the downfall of the Caliphate in the thirteenth century this accumulation of philosophical ideas and of primitive technology and science, coming from the ancient civilisations of the Near East, and from Persia, India and Greece, was inherited and developed by the Muslim alchemists. At the same time the Greek writings were hailed with enthusiasm and translated into Arabic. It was not until about the twelfth century A.D., that the accumulated knowledge of the Muslim alchemists, drawn from these diverse sources and augmented in its passage through Islam, began to percolate into Western Europe, chiefly via Spain and through the medium of Latin translations of Arabic texts. In one of the earliest of these translations, entitled *Liber de compositione alchemiae* ('Book of the Composition of Alchemy'), the translator, Robert of Chester, wrote in 1144: 'Since what Alchymia is, and what its composition is, your Latin world does not yet know, I will explain in the present work.'

It was in this roundabout way that ancient Greek writings passing through Arabic versions, came after many centuries into Western Europe in a Latin dress.

The Nature of Alchemy

Most people who think about alchemy in the present age (and there are not many who do) dismiss it as the pretended art of transmuting base metals, such as tin and lead, into the noble ones, silver and gold (known as 'noble' because of their permanent lustre). This perfunctory view may be set beside that of the great German chemist, Liebig (1803-73), who asserted that alchemy was never anything different from chemistry; so that to him it was essentially the chemistry of the Middle Ages.

In its widest interpretation, however, alchemy was a grandiose philosophical system which aimed at penetrating and harmonising the mysteries of creation and of life. It sought to bring the microcosm of man into relation with the macrocosm of the universe. The transmutation of one form of inanimate matter into another, placed in this larger context, was merely an incidental aim of alchemy, designed to afford proof on the material plane of its wider tenets, in particular that of the essential unity of all things. Alchemy was much more than a rudimentary form of experimental science.

The more one studies the wider aspects of alchemy, the more complex and bewildering the subject appears. Alchemy was indeed a vast network in which the sparse strands of rudimentary chemistry were interwoven with threads derived from ancient and later religions, folklore, mythology, astrology, magic, mysticism, philosophy, theosophy, and other wide fields of human imagination and experience. In recent times the associations of alchemy with religion and with psychology have formed the subject of much study, as an outcome of which it appears that alchemy is no less important to psychology than to chemistry.

At a conservative estimate, alchemy endured for more than a millennium, that is to say, from at least early Christian times until the end of the seventeenth century. Its influence upon human thought throughout this immense historical period was very great; but alchemy has been outmoded for several centuries, and so there is little realisation at the present day of the extent to which alchemical conceptions and imagery permeated the thought, the writings, and the art of the Middle Ages.

Alchemical Theory

Like modern science, alchemy had its guiding principles and ideas, although in detail these were subject to modifications and varying interpretations, often at the whim of the individual exponent. In broad outline it may be said that alchemical reasoning was mainly deductive and based upon two *a priori* assumptions: first, the unity of matter; secondly, the existence of a potent transmuting agent, known as the Philosopher's Stone. This so-called 'medicine of the metals' was held to be capable of curing the imagined diseases of the base metals, thereby ennobling them to the perfect metals, silver and gold. From the postulate of the unity of matter it followed that such an agent should also be effective in healing the infirmities of man and prolonging his life. In this guise the Philosopher's Stone was regarded as the perfect medicine of man, under the name of the *Elixir Vitae*, or Elixir of Life.

Thus, according to alchemical theory, all forms of matter are one in origin; these forms are produced by evolutionary processes; matter has a common soul which alone is permanent, the body, or outward form, being merely a mode of manifestation of the soul and therefore transitory and transmutable into other forms. In their essentials these views bear a close resemblance to those of modern physical science. Indeed, in the twentieth century, 'modern alchemy,' to use a term coined by Rutherford, has shown the possibility of bringing about many transmutations of elements.

In modern parlance it would be correct to call the Philosopher's Stone a catalyst. Here again the alchemists are vindicated: for what more potent catalyst could be imagined than the neutrons which start and maintain the explosive disintegration of uranium-235 into other elements? 'Every thing possible to be believ'd,' wrote the English poet and mystic, William Blake, 'is an image of truth .... What is now proved was once only imagin'd.'

As already mentioned, the idea of transmutation is implicit in the theory of the Four Elements. Moreover it was believed that properties, or qualities, such as colour or liquidity, could be imposed upon matter. Since gold and copper stand out as coloured, or 'tinted,' metals, it would consequently appear that a modification of the colour of copper could give rise to gold; and it has been thought that experiments to this end may have been undertaken in the Copper Age, earlier than 1200 B.C. Much later, in the third or fourth century A.D., some such process is indicated

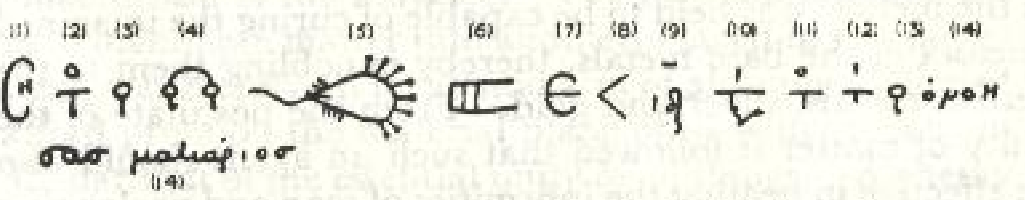


Fig. 3. The Formula of the Crab (Zosimos)

in the Greek writings of Zosimos of Panopolis, whose intriguing Formula of the Crab (Fig. 3) was probably a cryptic workshop recipe used by Egyptian craftsmen in making imitative gold by the use of copper salts, although the Formula has sometimes been held to conceal the secret of transmutation.

The conviction that metals should seek to attain the noble state of gold would be received without difficulty by the Aristotelians, in their belief that Nature strives towards perfection, and also by the Platonists, who held that nothing exists which is not inherently good. The further conceptions of the Philosopher's Stone and the Elixir of Life, as agents bringing such perfection to the inanimate and animate world, appear to have arisen as a natural extension of the Greek ideas; the same conceptions may also be related to the Arab belief and great interest in magic and magical agents.

The Stone was often described as a red powder, and it was no doubt sometimes confused with the red ore, cinnabar. This is a naturally occurring form of mercury sulphide, which when heated yields metallic mercury (liquid quicksilver) and evolves sulphureous fumes (sulphur dioxide), identical with those arising in the burning of native sulphur. It seems possible that experiments of this kind may have led the Muslim alchemists to put forward the so-called 'Sulphur-Mercury Theory' of the origin of metals. The most famous of these alchemists was Jabir ibn Hayyan, known to the Western world as Geber. He is said to have lived in the eighth century A.D., and the theory is often associated with his name. The same may be said of numerous alchemical treatises which were undoubtedly written after his time.

The Sulphur-Mercury Theory

The Muslim alchemists adhered essentially to the Aristotelian philosophy, although they modified it in certain ways. In particular, the sulphur-mercury theory appears basically as a derivative of the theory of the Four Elements. The apposition of the two opposed, or contrary, elements, fire and water, now assumed a new guise. 'Fire' became 'Sulphur,' and 'Water' became 'Mercury.' These names must not be identified with the material substances, sulphur (brimstone) and mercury (quicksilver). They denoted abstract principles, composed of hot and dry (sulphur) and cold and moist (mercury) 'natures.' In alchemical writings they were often called 'sophic' (or philosopher's) sulphur and 'sophic' mercury, or 'our' sulphur and 'our' mercury, in order to distinguish them from the material substances bearing the same names. In the main, sophic sulphur stood for the property of combustibility or the spirit of fire, and sophic mercury for that of fusibility or the mineral spirit of metals.

It was a common practice of alchemical writers to assume famous names in order to lend authority to their pronouncements. One of them, calling himself 'Roger Bacon,' living probably in the fourteenth century, gave an intelligible summary of the sulphur-mercury theory in the following words: 'The natural principles in the mynes are *Argent-vive* [Mercury] and *Sulphur*. All mettalls and minerals, whereof there be sundrie and divers kinds, are begotten of these two: but I must tel you, that nature alwaies intendeth and striveth to the perfection of Gold: but many accidents coming between change the mettalls. . . . For according to the puritie and impuritie of the two aforesaid principles, *Argent-vive* and *Sulphur*, pure and impure mettalls are ingendred.'

That is to say, according to medieval alchemical thought, when the impure principles, sulphur and mercury, were conjoined in natural processes under planetary influences they gave rise to base metals, such as tin and lead; when they were of high purity they gave silver or gold; but when each of the two principles was of superfine purity they yielded the Philosopher's Stone. Thus the Stone was so much purer than ordinary 'gold from the mines' that a small quantity of it could, by virtue of a species of leavening, transmute or 'tinge' an indefinite quantity of a base metal into ordinary gold.

In terms of the pictorial symbolism which forms so important a characteristic of alchemy, the sulphur-mercury theory is well illustrated in an engraving of 1617 (Fig. 4). The two kinds of principles or natural exhalations supposed to exist in the interior of the earth are marked with the familiar alchemical symbols for sulphur (left) and mercury (right). They are shown coming into conjunction in the bowels of the earth, and taking part in the imagined process whereby 'pure and impure mettalls are ingendred.' On the outer crust of the earth an alchemist with his apparatus is depicted as engaged in experimental attempts to imitate and accelerate these slowly occurring processes of Nature.

The chief experimental task of the alchemical adept was indeed to imitate and surpass Nature in accomplishing such changes: fundamentally therefore his position was closely akin to that of the modern chemist.

Alchemical Representations of the Sulphur-Mercury Theory

In the cryptic expression and symbolic representation which characterised alchemy and found a later expression in the symbols and formulae of modern chemistry, sophic sulphur and sophic mercury assumed a bewildering variety of forms. For example, they were known as Osiris and Isis, sun and moon, Sol and Luna, brother and sister, masculine and feminine, active and passive, giver and receiver, seal and wax, fixed and volatile, wingless lion and winged lioness, lion and eagle, and so forth. The Stone, when conceived as the result of the union of masculine and feminine principles, was sometimes represented as an infant.

As an outcome of the sulphur-mercury theory it was often supposed by the adepts, or esoteric (informed) alchemists that the pure 'seeds' of gold and silver (Sol and Luna) could be extracted from these noble metals in the form of sophic sulphur and sophic mercury. The 'seeds' could then be combined, often through the medium of a liquid menstruum, to yield the Philosopher's Stone. The succession of practical processes here concerned was known as the Great Work, leading to the final goal of the Grand Magisterium, or Philosopher's Stone.

According to these views, which were avidly adopted by pretended goldmakers, an initial quantity of gold was necessary in order to enter upon the operations of the Great

Work. The Stone could then be used in converting base metals into more gold, so that the original gold was 'multiplied,' as the alchemists were wont to say. One of their favourite metals for 'multiplication' was mercury; and this choice has been curiously vindicated by modern observations that gold can really be produced by transmutation from mercury, although only in excessively minute amounts and at great cost.

Alchemical literature abounds in cryptic descriptions and pictorial representations of the blending of sophic sulphur and sophic mercury in the synthesis of the Stone. These designs often symbolise the remote and proximate materials of the Stone, together with the conjoining menstruum, usually known as the Hermetic Stream, 'philosophical water,' or 'heavy water.' As a rule, the remote materials are gold and silver (Sol and Luna); the proximate ones are sophic sulphur and sophic mercury, symbolised as shown in Fig. 4. In a typical design a wingless lion and winged lioness are shown in playful conflict against a watery background, again suggestive of the menstruum.[1]

In terms of the Aristotelian theory, the conjunction of sophic sulphur and sophic mercury would correspond to the union of fire and water, whereas the Greeks held that combination between contraries was impossible. There is, however, a typical alchemical engraving of 1617 showing an alchemist (purporting to be Roger Bacon) in the act of balancing two pans containing these ancient enemies.[2] According to an accompanying comment: 'When thou shalt make equal the weights of the elements, thou wilt behold with thine eyes welcome gifts.' Once again, the river in the background suggests the Hermetic Stream in which sophic sulphur and sophic mercury are to be conjoined. Sometimes this Hermetic Stream was depicted as the Bath of the Philosophers, in which Sol and Luna disported themselves jointly (Fig. 14).

[1] *Prelude to Chemistry,* Plate 57 (i). [2] *Ibid.,* Plate 41 (ii).

By distilling wine, probably in Italy in the ninth or tenth century, the discovery was made of almost pure alcohol. Since this substance is a 'water' (i.e. liquid) which also burns, it was hailed by some of the alchemical fraternity as the achievement of their goal of conjoining water and fire, thus squaring the alchemical circle. Some also viewed this so-called *aqua vitae* as the end of their search for a solvent for the Philosopher's Stone, in the preparation from it of the *Elixir Vitae.* 'The taste of it,' wrote an unknown and enthusiastic adept, taking to himself the famous alchemical name of Lully, 'exceedeth all other tastes, and the smell of it all other smells.' This writer, a pseudo-Lully, even saw in the production of so potent a spirit a sign of the approaching end of the world.

The view of the sulphur-mercury theory as a union of masculine and feminine principles found an expression in various pictorial representations of the so-called Hermetic Androgyne, Rebis, or Two-Thing. These designs, like so many others in alchemy, were often delicately coloured; for example, the masculine and feminine half-figures of the hermaphrodite standing beside the sun-tree (yellow) and moon-tree (blue), signified 'multiplication'; and a dragon at the foot represented the liquid menstruum.

Fig. 5. Leto (Latona), with Apollo and Artemis, and the Python

Incidents from the Bible and from classical mythology were also freely interpreted in terms of alchemical theory and ideas. Thus, in an alchemical manuscript with copious painted illustrations, contained in the St. Andrews collection, the birth of Eve from Adam's rib, with the Serpent as onlooker, is depicted to symbolise the same fundamental idea as the Hermetic Androgyne.[1]

As an example of another kind (Fig. 5), the story of Apollo (Sol) and Artemis (Luna), with the terrorising Serpent (menstruum) of the jealous Juno, is selected from classical mythology in order to furnish a further illustration of the same theme.

The Emerald Table of Hermes

The informed alchemists, or adepts, regarded their esoteric doctrines as a sacred trust to be maintained as a closed body of knowledge from uninformed or exoteric practitioners who sought only to obtain wealth as gold-makers, either by 'milking' wealthy patrons or through hitting by a lucky chance upon the secret of transmutation. The adepts based their 'noble practise' largely upon a series of thirteen precepts, said to have been engraved upon an Emerald Table. One of the many apocryphal legends, to which alchemists were much addicted, stated that this *Tabula Smaragdina*, inscribed with Phoenician characters, was brought to light from the tomb of Hermes by Alexander the Great, or, alternatively, that it was taken from the hands of the dead Hermes in a cave near Hebron, some ages after the Flood, by Sarah the wife of Abraham.

Fig. 6. Hermes Trismegistos

Hermes Trismegistos (Fig. 6), or Hermes the Thrice-Great, the Greek counterpart of the Egyptian god, Thoth, was revered by the adepts of alchemy as the father of their 'Hermetic Art,' and the patron of its practitioners. For this reason they often styled themselves the 'sons of Hermes.'

[1] *Humour and Humanism in Chemistry*, Fig. 3.

In actual fact, the earliest record yet known of the precepts of the Emerald Table came to light as recently as 1923 in a corrupt Arabic version, in a work ascribed to Jabir, or Geber. Probably this statement of alchemical doctrine, known hitherto only in medieval Latin, goes back much further than this source, and it certainly constitutes one of the oldest alchemical fragments extant.

It is thought that the *Tabula* may have been written originally in Syriac. These precepts of Hermes were cherished with a kind of religious fervour by the adepts, who looked upon them as summarising in a concealed form the fundamental secrets of alchemy and of the Philosopher's Stone. The *Precepts of the Emerald Table of Hermes* run in this wise:

1. I speak not fictitious things, but that which is certain and true.
2. What is below is like that which is above, and what is above is like that which is below, to accomplish the miracles of one thing.
3. And as all things were produced by the one word of one Being, so all things were produced from this one thing by adaptation.
4. Its father is the sun, its mother the moon; the wind carries it in its belly, its nurse is the earth.
5. It is the father of perfection throughout the world.
6. The power is vigorous if it be changed into earth.
7. Separate the earth from the fire, the subtle from the gross, acting prudently and with judgment.
8. Ascend with the greatest sagacity from the earth to heaven, and then again descend to earth, and unite together the powers of things superior and inferior. Thus you will obtain the glory of the whole world, and obscurity will fly away from you.
9. This has more fortitude than fortitude itself, because it conquers every subtle thing and can penetrate every solid.
10. Thus was the world formed.

11. Hence proceed wonders, which are here established.
12. Therefore I am called Hermes Trismegistos, having three parts of the philosophy of the whole world.
13. That which I had to say concerning the operation of the sun is completed.

A careful examination of these seemingly oracular pronouncements shows that they do in fact summarise in a veiled form the main features of alchemical theory. The second and third precepts refer to the doctrine of the unity of all things; the fourth precept embodies the ideas of the masculine and feminine principles of the sulphur-mercury theory, and the four elements of Aristotle, fire (sun), water (moon), air (wind) and earth. The fifth precept conveys the Greek conception of progress towards perfection; the seventh is suggestive of alchemy as the 'art of separation' (*Scheidekunst*); and the eighth adumbrates the circulation of the proximate materials within the sealed Vessel of Hermes, in the last stages of the Great Work of preparing the Philosopher's Stone and attaining the 'glory of the whole world.'

The Tria Prima *of Paracelsus*

Alchemical theory was essentially static throughout the medieval period. The long line of verbose writers on alchemy had little new to bring forward, beyond variants of cryptic and pictorial expression, until the time of Paracelsus (1493-1541). Predominantly, Paracelsus was the herald of a new era, an era of iatrochemistry, or chemistry applied to medicine (p. 98). His contribution to alchemical theory lay in the addition to sulphur and mercury of a third principle, which he called 'salt.' Materially this was recognised as the principle of uninflammability and fixidity.

Now, in the alchemical mind, the material and spiritual ingredients of alchemy were indissolubly united. Indeed, to take a wider view, until the day of Descartes, in the seventeenth century, men drew no rigid distinction between matter and mind. Until about the time of the decline of alchemy, it had been supposed throughout the ages that gross or tangible matter took shape in progressively finer forms, ranging through mists, smokes, exhalations, air, and the so-called ether, to animal spirits, the soul, and spiritual beings. There was supposed to be an essential unity of all things, whether tangible or intangible, material or spiritual. This conception found expression, for example, in an ancient Greek inscription associated with the Ouroboros, or tail-eating serpent (Fig. 7): 'One is all, and by it all, and to it all, and if one does not contain all, all is nought.'

Fig. 7.
The Ouroboros Serpent, or 'Tail-Eater'

So the *tria prima*, or three 'hypostatical principles' of Paracelsus had a double significance: they could be interpreted in either a material or a spiritual sense. In the words of Paracelsus himself: 'Know, then, that all the seven metals are born from a threefold matter. . . . Mercury is the spirit, Sulphur is the soul, and Salt is the body . . . the soul, which indeed is Sulphur . . . unites those two contraries, the body and spirit, and changes them into one essence.' The soul, according to this pronouncement, plays here a spiritual part similar to the material effect of the liquid menstruum, or Hermetic Stream, in uniting sophic sulphur and sophic mercury to produce the Philosopher's Stone. It would be in closer accord with alchemical theory to represent the two contraries by sulphur (soul) and mercury (spirit). Such a correlation is depicted in an attractive alchemical engraving of 1625 showing two fishes swimming in the sea, with an appended legend in Latin: 'The sea is the body, the two fishes are the spirit and the soul.' The *tria prima* found many other forms of graphic expression, notably as the alchemical triangle composed of three lines or three serpents (Fig. 8).

The chief relationships of the *tria prima* may thus be represented as in the following summary:

Mercury	*Sulphur*	*Salt*
Metallicity, liquidity	Inflammability	Uninflammability
Volatile, but unchanged in the fire	Volatile, and changed in the fire	Found in the ashes
Spirit	Soul	Body
Water	Air and Fire	Earth

Fig. 8. The Alchemical Triangle

When considered as masculine and feminine principles, sulphur and mercury were regarded as fixed and volatile, respectively, a connotation that seems at variance with this scheme. Here is another inconsistency; but if alchemy had an extra principle it was certainly not consistency.

In another place, Paracelsus called his three principles phlegma, fat and ash: 'The phlegma is Mercurius, the fat is Sulphur, and the ash is Salt. For that which smokes and evaporates over the fire [as in the burning of wood] is Mercury; what flames and is burnt is Sulphur; and all ash is Salt.' In this particular interpretation of the *tria prima* may be found a faint foretokening of the later theory of phlogiston (p. 120). Here is an example, drawn from alchemy, of the truth of the ancient proverb that old sins have long shadows.

III · THE PHILOSOPHER'S STONE

The Mainspring of Alchemy

THE conception of the Philosopher's Stone was the mainspring of alchemy. It provided an unexampled motive power, a kind of alchemical perpetual motion, which animated some forty generations of alchemists. The story of this imagined Stone and the allied Elixir of Life is the most enduring and romantic epic to be found in the whole history of science.

The nature of the quest was expressed succinctly by the celebrated alchemist and physician, Arnold of Villanova, at about the opening of the fourteenth century, in the following words: 'That there abides in Nature a certain pure matter, which, being discovered and brought by Art to perfection, converts to itself proportionally all imperfect bodies that it touches.' The idea had originated long before that time: when, it is impossible to say. Perhaps it was formed at Alexandria in the early centuries of the Christian era, under the fostering influence of the magical beliefs and practices of ancient Egypt and of the later neo-Platonists and Muslims. The dual conception of the magic Stone and the magic Elixir may be viewed also as a link between the prevailing theories of the constitution of matter and the spiritual ideas relating to the regeneration of man. The Stone, together with the derived Elixir, was pictured, in the words of the Emerald Table, as 'the father of perfection throughout the world.' Since the Aristotelians held that Nature strives always towards perfection, it seemed logical to suppose that an agent promoting such a process should exist in Nature.

The achievement of the Great Work of preparing the Stone was the final and dazzling goal of alchemists of all degrees. To the religious mystics among them the quest appeared as imperfect man's striving towards perfection; to the mercenary alchemists, at the other end of the scale, it opened up a vista of wealth beyond the dreams of avarice. In the words of Goethe, 'Gold gives power; without health there is no enjoyment, and longevity here takes the place of immortality.' To many at the present day, the quest of the Stone may appear as no more than a misplaced obsession, a useless and time-consuming chimera: in fact, however, the development of modern science owes an incalculable debt to the tedious, untiring and unrewarded application to unpleasant tasks of so many generations of 'labourers in the fire,' as the working alchemists were often called.

In the end, these wearisome labours, apparently so barren, brought forth a rich and unexpected harvest by opening an entry into the modern science of chemistry. In the words of the great German chemist, Liebig: 'The most lively imagination is not capable of devising a thought which could have acted more powerfully and constantly on the minds and faculties of men, than that very idea of the Philosopher's Stone. Without this idea, chemistry would not now stand in its present perfection. . . . In order to know that the Philosopher's Stone did not really exist, it was indispensable that every substance accessible . . . should be observed and examined. . . . But it is precisely in this that we perceive the almost miraculous influence of the idea. The strength of opinion could not be broken till science had reached a certain stage of development.'

The descriptions of the elusive Stone, which nobody had ever handled or even seen, were numerous and various. It was often mentioned as a heavy, shining powder, with a strong and pleasant odour. This 'powder of projection,' when red in colour, could transmute into gold; when white, only into silver. In general, the alchemists attached great importance to colour and change of colour. Indeed, transmutation was sometimes called 'tingeing.' '*Mare tingerem, si mercurius esset!* I would tinge the sea, were it mercury!' exclaimed the pseudo-Lully. This claim, couched in the grandiloquent language of alchemy, conveyed also an idea of the supposed transmutative potency of the Stone.

Preparation of the Stone

The alchemists delighted in paradox. They were much given to contradictory statements, which are sometimes referred to more politely as ambivalent ideas. Notably, they held that although the Stone was infinitely difficult to attain, yet it lay at hand, diffused throughout Nature and awaiting anybody having the clear alchemical vision enabling him to pick it up. For example, an alchemical engraving of 1618 shows the Stone (depicted as a solid rectangular block) lying on the earth, drifting in the water, and floating in the sky; yet imperceptible to the unseeing passers-by. The *Gloria Mundi*, an alchemical work of about a century earlier (1526), had stated that the Stone 'is familiar to all men, both young and old, is found in the country, in the village, in the town, in all things created by God; yet it is despised by all. Rich and poor handle it every day. It is cast into the street by servant maids. Children play with it. Yet no one prizes it, though, next to the human soul, it is the most beautiful and the most precious thing upon earth, and has power to pull down kings and princes. Nevertheless, it is esteemed the vilest and meanest of earthly things.'

From all this, it ought to have been evident to the uninformed, or exoteric, alchemists, that they stood a very poor chance of reaching the goal: since presumably even if by good luck they achieved the Stone they would fail to recognise it! On the other hand, the informed adepts, or esoteric alchemists, the self-styled 'Sons of Hermes,' guided by the enigmatic precepts of the Emerald Table and a complicated body of equally cryptic information and directions, were confident of ultimate success, provided

Fig. 4. A Representation of the Sulphur-Mercury Theory of Metals

(See p. 20)

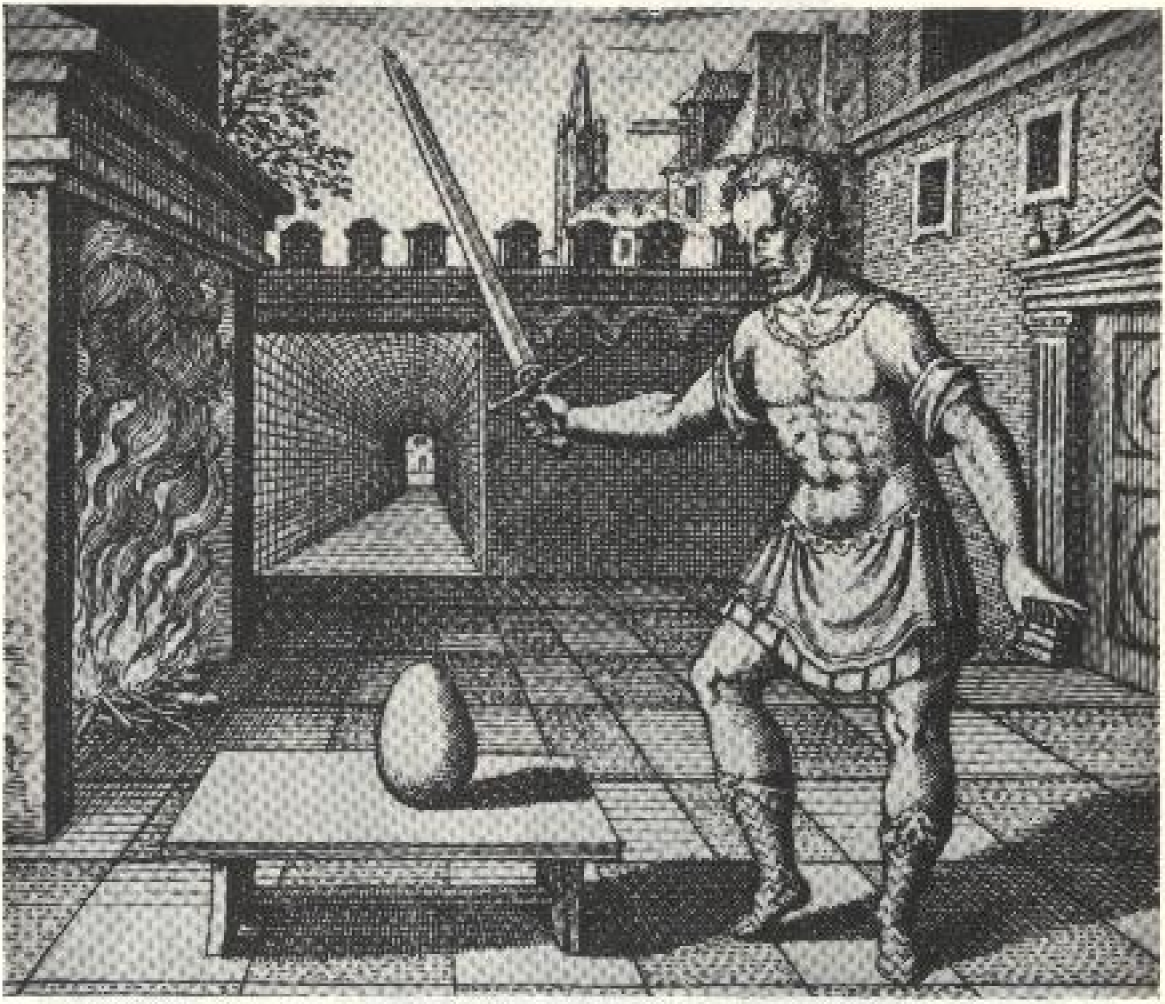


Fig. 10. (*above*) The Egg and Fiery Sword

(*See p. 36*)

Fig. 11. The Hermetic Vessel in the Athanor

(*See p. 36*)

that they were able to co-ordinate a complex set of conditions and influences.

Descriptions of the operations of the Great Work are as numerous as they are difficult to disentangle and reduce to an intelligible form. Moreover, confusion becomes even worse confounded owing to the concealed or symbolic rendering of the directions. The preliminaries to the operations of the Great Work proper consisted in purifying certain so-called primitive materials, from which the proximate materials were then obtained by the application of further processes of a chemical nature. The favourite primitive materials, although many others came into the innumerable experiments, were gold and silver. Purified gold and silver yielded sophic sulphur and sophic mercury, respectively, also known under many other names. These proximate materials were then brought together in the Hermetic Vase, or Philosopher's Egg. This glass vessel was then 'hermetically sealed' in a flame and submitted to the processes and influences of the Great Work proper. Sometimes a third proximate material, known as sophic salt (or 'magnesia') and often prepared from quicksilver, came into the scheme, to complete an alchemical trinity.

It may be presumed that the materials mentioned above were such as would normally be used by an adept belonging to the esoteric fraternity of the 'Sons of Hermes'; but the uninformed exoteric practitioners of alchemy brought many others into play, as Liebig recognised when he wrote that 'it was indispensable that every substance accessible . . . should be observed and examined.' Chaucer, in referring to a fourteenth-century alchemist of this kind, mentions,

> Arsenek, sal armoniak, and brimstoon.
> And herbes coude I telle eek many a one,
> As egrimoigne, valerian, and lunarie,
> And other suche, if that me list to tarie . . .
> Unslekked lyme, chalk, and glare of an ey,
> Poudres dyvers and asshes, dong, and cley,
> Ceréd poketts, sal petre, vitriole;

And dyvers fyres made of woode and cole;
Salt tartre, alcaly, and salt preparat,
And combust materes, and coagulat;
Cley made with hors or mannes hair, and oyle
Of tartre, alym, glas, barm, wort, and argoyle.

Processes of the Great Work

The operations even of the esoteric alchemists were subject to wide variations; but the central and crucial feature of the Great Work consisted in a prolonged and controlled heating of the proximate materials, under the right conditions, in the sealed vessel of Hermes. Thereafter it was often supposed that the potency of the Stone could be greatly enhanced in the process called 'multiplication.' Finally, the 'multiplied' Stone was added to the fused base metal in the crowning operation of 'projection,' thereby bringing about a rapid and spectacular transmutation. *Finis coronat opus!*

The endless accounts of what was supposed to take place in the Hermetic vessel and in subsidiary operations contain a profusion of processes, differing from writer to writer in their number, nature and order. Paracelsus held that only seven processes were necessary. George Ripley, Canon of Bridlington, in Yorkshire, writing in the fifteenth century, laid down twelve processes in his *Compound of Alchymie . . . Conteining twelve Gates*. Another sequence of twelve processes mentioned by Pernety and each related to a sign of the Zodiac, is given below:

1.	Calcination .	♈	Aries, the Ram
2.	Congelation .	♉	Taurus, the Bull
3.	Fixation .	♊	Gemini, the Twins
4.	Solution .	♋	Cancer, the Crab
5.	Digestion .	♌	Leo, the Lion
6.	Distillation .	♍	Virgo, the Virgin
7.	Sublimation .	♎	Libra, the Scales
8.	Separation .	♏	Scorpio, the Scorpion
9.	Ceration .	♐	Sagittarius, the Archer
10.	Fermentation	♑	Capricornis, the Goat

11. Multiplication ♒ Aquarius, the Water-carrier
12. Projection ♓ Pisces, the Fishes

Some of the names of these and other processes of the Great Work are used in modern chemistry with little alteration of meaning; but others are obsolete. 'Calcination,' or heating in air, led to the 'fixation' of fusible metals whereby they assumed a permanently solid form, or 'calx,' which resisted further change. 'Distillation' was often depicted as a two-fold process, consisting of 'ascension' and 'descension,' symbolised by birds in upward or downward flight. Similarly, 'sublimation' was represented by swans, doves, and other birds flying upwards. Repeated sublimation was supposed to furnish the quintessence of the sublimed material. Solution, fixation, and sublimation were considered of such importance that Glauber, in the seventeenth century, summarised the preparation of the Stone in the following couplet:

Dissolve the Fixt, and make the Fixèd fly,
The Flying Fix, and then live happily.

'Putrefaction,' or 'mortification,' were terms applied to the 'death' of a metal, usually through the agency of heat (oxidation); the reverse process of 'revivification,' or 'resurrection' (reduction), was seen by the alchemists as the restoration of the soul of a metal to its body. These two changes were supposed to be shown by the respective appearance of black and white colours. According to a widespread alchemical idea, even gold, the perfect metal, had to be mortified in order to enable its 'seed' to germinate or grow, when brought into a suitable medium. 'The grain and all vegetable seed, when cast into the ground, must decay before it can spring up again,' wrote Paracelsus, in quoting a common medieval misconception. The process of 'conjunction' was regarded as the union, or marriage, of male and female, Sol and Luna, sulphur and mercury, fixed and volatile, toad and eagle, and so forth. In 'cibation,' the vessel was fed with fresh material.

'Circulation' was a continuous form of distillation in a closed vessel. This process was often carried out in a two-armed pelican (Fig. 9), or sometimes in a double pelican. Cibation was also linked with the fable of the pelican nourishing its young with blood trickling from its own breast (Fig. 9).

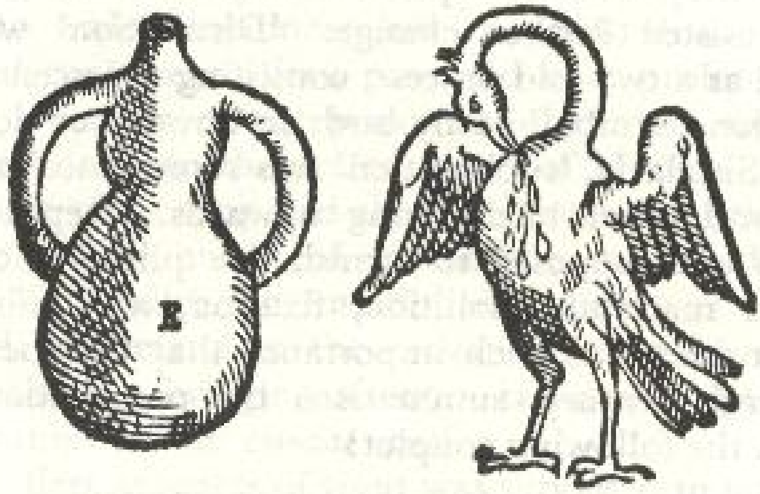


Fig. 9. The Alchemical Pelican

Of the many other common names applied to alchemical operations, there were two of peculiar importance, because they were applied to the last two of the series of processes culminating in transmutation. According to a fundamental chemical tenet, the Stone, or powder of projection, when obtained in its first form would be increased enormously in potency by a process of 'multiplication.' Here again, some confusion is apt to arise; because the same term was used by the goldmakers to signify the augmentation of an original supply of gold by using it as a starting point in transmutative experiments. Ripley stated that the Medicine (Stone) could be multiplied 'infynytly' with mercury, ten parts 'being multyplyed lykewys, Into ten thousand myllyons, that ys for to sey, Makyth so grete a number I wote not what yt ys.'

Subtle, in Ben Jonson's play, *The Alchemist* (1612), expresses the same idea when he says:

I exalt our med'cine,
By hanging him in *balneo vaporoso*,
And giving him solution; then congeal him;
And then dissolve him, then again congeal him;
For look, how oft I iterate the work,
So many times I add unto his virtue.
As, if at first one ounce convert a hundred;
After his second loose, he'll turn a thousand;
His third solution, ten; his fourth, a hundred.
After his fifth, a thousand thousand ounces
Of any imperfect metal, into pure
Silver and gold.

In the final operation of 'projection,' a tiny amount of the precious powder, usually wrapped in paper or enclosed in wax, was thrown into the midst of a heated crucible containing the quicksilver, molten lead, or other material to be transmuted. The pseudo-Roger Bacon claimed that the perfect Stone was able to transmute a million times its own weight of a base metal into gold of ordinary purity; another alchemist, writing under the name of Philalethes, in his *Guide to the Celestial Ruby*, modestly refrained from giving a higher figure, and contented himself by saying that 'your arithmetic will fail sooner than its all-prevailing power.'

The Vase of Hermes

The operations of the Great Work found their consummation in the hermetically sealed Vessel known in alchemy under many names, notably as the Vase of Hermes, the Vase of the Philosophers, or the Philosopher's Egg. In shape it resembled a pear rather than an egg; but the pear had no alchemical significance, whereas the egg was the symbol of creation or of fertility. Indeed, the Vessel was also regarded as a brooding house or incubator, under the name of the House of the Chick. Among its other names were the House of Glass and the Prison of the King.

Usually the description of the vessel and of the experimental conditions to which it was subjected were couched in nebulous and obscure language or represented by symbolical drawings. Just as the Vessel itself was hermetically sealed, so was everything pertaining to it guarded by the 'Sons of Hermes' as a sealed body of knowledge and ritual, sacred to these priests of 'the Divine Art.' It was certainly not to alchemical writings that the tyro of alchemy could turn for clear experimental directions. If he did so, the best he could hope for would be an illustration after the manner of Fig. **10**, with the illuminating advice to aim at the egg 'carefully, as is the custom, with the fiery sword; let Mars lend his aid to Vulcan, and thence the Chick arising will be conqueror of iron and fire.' A manual of practical chemistry based on this model would be intriguing rather than informative to the modern student; but to the adept the indication was clear enough. In alchemical parlance, the sword and other sharp and wounding instruments denoted fire: thus Mars and Vulcan are iron and fire, and the Chick is the Philosopher's Stone.

This symbolic engraving appeared in 1618; but later on the secrets began to leak out, and a straightforward illustration with precisely the same meaning was given a hundred years afterwards in Barchusen's *Elementa Chemiae* (Leyden, 1718). This shows the heating of the sealed Vessel in an athanor, or alchemical furnace, fired by charcoal (Fig. **11**).

The adepts attached special importance to fire, their chief agent, which they often personified as Vulcan, or Hephaestus: this fire-god, having been born lame, was sometimes depicted as a man with a wooden leg. A distinction was often drawn between celestial, or creative, fire, and common elemental fire, held to be destructive in its effects. There were various regimens, or degrees, of fire (or heat), rising from that of a brooding hen through the water-heat of a water-bath (or *bain-marie*), and the sand-heat of a bath of sand or ash, to the naked heat of a bare fire. Norton, the fifteenth-century alchemist of Bristol, wrote that 'nothing may let [hinder] more your desires, Than ignorance of Heates of your Fiers.' According to him, 'Gebars Cookes' [Geber's cooks], as he contemptuously termed the exoteric alchemists, were woefully lacking in this matter, despite their absorption in books. He held that 'A parfet *Master* ye maie him call trowe, Which knoweth his Heates high and low.'

Norton himself invented a new kind of furnace, which apparently provided an improved adjustment of heat (temperature). Of this he wrote, after the secretive manner of the adepts, in his *Ordinall of Alchimy* (1477):

> Which suttill Furnace I devised alsoe,
> In which I found manie wonders moe
> Than is convenient at this season to tell.

The processes taking place within the Philosopher's Egg were often likened to incubation, and therefore time was accounted a significant factor. Count Michael Maier, writing in 1617, held that 'Nature's time is extremely long, and the fashion of her concoction is uniform, and her fire very slow. That of Art, on the other hand, is short; the heating is controlled by the wit of the artist, as the fire also is made intenser or milder.' Sometimes, from a supposed mystical relationship with the seven metals of alchemy and the seven major heavenly bodies, the operations were limited to seven, occupying seven days. A so-called 'philosopher's month' of forty days was often adopted. Still longer periods were indicated in the statement that the regimen of Saturn, or blackness, alone lasted from the fortieth to the ninetieth day.

In modern chemical processes, the nature and proportions of the reacting materials, the physical conditions of the experiment, and the time, are all carefully laid down. Such a prescription held also for the operations of the Great Work, except that little or no attention was usually given to proportions. The requirements of the Great Work, however, were much more complicated and exacting than those of modern practical chemistry.

Particular attention had to be given to the astrological influences prevailing throughout its duration. It was held that the terrestrial operations had to be harmonised with celestial influences. According to Norton, the preparation of the Stone must begin with the Sun in the zodiacal sign of the Archer and with the Moon in that of the Ram; and it must end under the conjunctive influence of the Sun and Moon in the Lion. Sometimes a sign of the Zodiac was allocated to each specific process (p. 32). Thus, Ben Jonson's alchemist, Subtle, observed:

> How is the moon now? eight, nine, ten days hence,
> He will be silver potate; then three days
> Before he citronise: some fifteen days
> The magisterium will be perfected.

Another great complication was bound up with the idea of the appearance of a definite sequence of colours during the progress of the Great Work. According to Basil Valentine, 'the Matter of the Sages passes through the several varieties of colour . . . as often as a new gate of entrance is opened to the fire.' Some adepts held the sequence to be black, white, citrine, and red, associated severally with the four elements and the four humours of the human body: earth and black bile, water and phlegm, air and yellow bile, fire and blood. Also, when a certain stage had been reached within the Hermetic Vase, the appearance of the rainbow colours of the peacock's tail assured the adept that he was on the right path. 'Betwixt Black and Whyte sartyne, The Pekokes fethers wyll appear plaine,' asserted Charnock in 1574.

Blackening denoted complete putrefaction; and, as Norton wrote in 1477, 'Red is last in work of *Alkimy*.' If red foreran black, the Work had gone astray, as also if 'the young ones of the crow went back to their nest,' in a return of the black colour later in the sequence. After recapitulating the colours of the Great Work in his *Twelve Gates*, Ripley added: 'And after all thys shall appere the blod Red invaryable, Then hast thou a Medcyn of the thyrd order of hys owne kynde Multyplycable.'

Still another factor which some of the mystical alchemists considered important in the operations of the Great Work was ascribed to the influence of music. This conception, arising from the Pythagorean emphasis upon number, harmony, and music, in the general scheme of the universe, reached its apotheosis in the writings of Count Michael Maier, and found its particular expression (p. 65) in his picturesque work, *Atalanta Fugiens* (1618). The supposed influence of suitable music upon the processes within the Hermetic Vase was linked quite logically with other alchemical conceptions (p. 68). Norton, in 1477, pointed out to the alchemical adept that just as 'accords which in Musick be, With their proporcions causen Harmony, Much like proportions be in *Alkimy*.'

Finally, even if the keen pursuer of the Stone were able to co-ordinate the chemical, physical, and astrological influences throughout the whole course of his operations; to produce the right colour sequence; and to provide a suitable musical accompaniment; he might still fall at the last fence and fail to reach the finish. There was another important and formidable condition: the operator had to be prayerful and pure of heart; or, to quote Ben Jonson's phrase, '*homo frugi*, a pious, holy, and religious man, one free from mortal sin, a very virgin.' That is why, in *The Alchemist*, owing to the lamentable backslidings of Mammon, Subtle told him at the crucial stage of the operations that the Great Work 'has stood still this half hour: and all the rest of our less works gone back.' Even as Subtle spoke, there came 'a great noise and crack within'; and Face, his assistant, rushed forward with the fatal announcement:

O sir, we are defeated! all the works
Are flown *in fumo*, every glass is burst!
Furnace and all rent down! as if a bolt
Of thunder had been driven through the house.
Retorts, receivers, pelicans, bolt-heads
All struck in shivers!

An engraving of the alchemical mystic, Heinrich Khunrath, shows him at his devotions in a large room, one side of which is fashioned as an oratory and the other as a laboratory. Again, the prayerful secrecy essential for the accomplishment of the Great Work lies embalmed in the alchemical aphorism: *Ora, Lege, Lege, Lege, Relege, Labora, et Invenies* ('Pray, read, read, read, read again, toil; and thou shalt find').

IV · ALCHEMICAL CRYPTICISM AND SYMBOLISM

FROM the very beginnings of 'the Divine Art' of alchemy, its esoteric practitioners used every known device of cryptic expression, allegory, and mystic and symbolic representation in order to 'vaile their secrets with mistic speech,' lest, as they put it, the clodhopper might turn from his plough in order to cultivate the more alluring Soil of the Sages.

The Symbols of Alchemy

Alchemy took over as an inheritance from pre-history the use of symbols for expressing abstract and ill-comprehended ideas. The earliest and most widely used alchemical symbols were those denoting the four elements and the seven metals. Although their origins are unknown, their shapes are often suggestive of the thing represented. In the symbols of the four elements (Figs. 12 and 20), the triangle of fire points upwards, suggesting sharp ascending particles; while that of water, the opposed element, points to the downward path of a ponderable particle. The barred, or laden, symbols of air and earth are indicative of increased weight as compared with the unbarred symbols of similar disposition.

The symbols for fire and sulphur (Fig. 20), together with the later symbol for phlogiston, show a continuity of the underlying idea: all three have the upward-pointing triangle; for sulphur a cross is added to the base of the simple triangle of fire; and for phlogiston a small circle is inserted in each angle of the symbol for sulphur.

The association of the heavenly bodies with the known metals and also with human organs and destinies goes back to ancient Chaldea, the land of astrologers. In Chaucer's words:

> The bodies seven, eek, lo heer anon.
> Sol gold is, and Luna silver we declare;
> Mars yron, Mercurie is quyksilver;
> Saturnus leed, and Jubitur is tyn,
> And Venus coper, by my fathers kyn.

The symbols of circle and crescent for the noble metals, gold and silver, are clearly derived from the familiar shapes of the two major heavenly bodies, to which the metals were assigned because of their colour and perfection. Quicksilver (Fig. 13), with a sign perhaps derived from the caduceus of the messenger of the gods, has a quick 'mercurial' movement, like that of the planet. The so-called looking-glass of Venus and the spear and shield of Mars, representing also feminine and masculine characters, have sometimes been assigned a phallic derivation: the symbol of Venus has also been likened to the *'ankh*, *crux ansata*, or handled cross of ancient Egypt (Fig. 6), denoting the Sun's life-giving force to things earthly. Iron was looked upon as the metal, and Mars as the planet, of war. Dull and heavy lead was linked with slow-moving Saturn, denoted by a symbol derived from the scythe of Saturn, or the initial of Kronos, 'old Father Time.' Tin, because of its brightness, was conjoined with the bright planet, Jupiter; moreover its 'crackle' when bent suggested the noise of Jove's thunderbolt; its symbol may have been derived from the thunderbolt, or from the Arabic sign of 4, or from the Greek initial letter of Zeus.

Corresponding names were bestowed upon salts of these metals by the alchemists, and some of them have persisted down to the present day. Some examples are: lunar caustic (silver nitrate); vitriol of Venus (copper sulphate); sugar of Saturn (lead acetate); and vitriol of Mars, or martial vitriol (ferrous sulphate).

In such fanciful ways an extensive system of symbols was gradually built up by the medieval alchemists to cover the many materials, processes and forms of apparatus concerned in their operations. As usual in alchemy, there was a lack of uniformity in the application of these symbols; even gold was represented in more than sixty ways. A short selection of such symbols, used in the seventeenth century, is shown in Fig. 12. To add to the confusion, the alchemical fraternity revelled in anagrams, acrostics, secret alphabets,

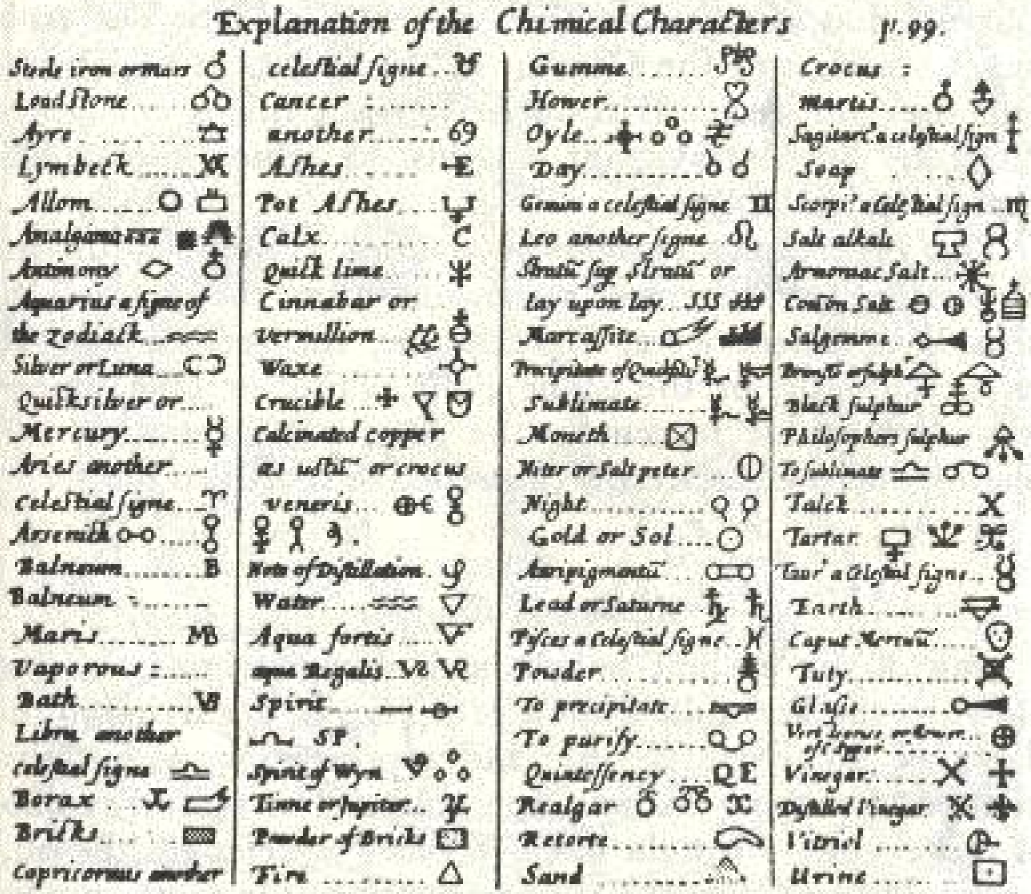


Fig. 12. Some 'Chimical Characters'

and ciphers. Moreover, they supplemented a grandiose system of pictorial symbolism with allegorical allusions. Their imaginations ran riot in representations of apparatus and operations by a welter of birds and animals—both real and mythical—figures culled from the ancient mythologies, geometrical designs, and other emblems in an almost unending variety.

As Liebig remarked, they 'propounded in an unintelligible language that which, in their own minds, was only the faint dawn of an idea.' Thus, Philalethes, doubtless in a mood of alchemical exaltation, described sophic mercury as 'our doorkeeper, our balm, our honey, oil, urine, may-dew, mother, egg, secret furnace, oven, true fire, venomous Dragon, Theriac, ardent wine, Green Lion, Bird of Hermes, Goose of Hermogenes, two-edged sword in the hand of the Cherub that guards the Tree of Life . . . it is our true, secret vessel, and the Garden of the Sages, in which our Sun rises and sets. It is our . . .'—but this is enough to illustrate the extravagant heights to which alchemical expression could aspire.

This efflorescent imagery was often coupled with distinctive colour schemes, somewhat after the manner of heraldry. There were, for example, the red king (gold, sophic sulphur, or the Stone); the white, or blue, queen (silver, or sophic mercury), the grey wolf (antimony sulphide), and the black crow (putrefied or mortified matter).

Alchemical Enigmas

One of the earliest known alchemical enigmas is provided by the Formula of the Crab (Fig. 3), occurring in the dawn of alchemy (p. 16), and representing a putative method of making an imitation gold. The second symbol of this cryptic Formula has been said to refer to 'the all,' or universal matter; the crab to fixation; the tenth symbol to the Philosopher's Egg; with the appropriate ending, 'blessed is he who gets understanding.'

The later alchemists held in superstitious reverence a so-called Riddle of the Stone, known as the Vitriol Acrostic (Fig. 13). This was often associated with the Emerald Table, and ascribed to the mysterious Basil Valentine. In it, around a central design, there is a Latin inscription signifying: 'visit the inward parts of earth; by rectifying thou shalt find the hidden Stone.' The initial Latin letters, VITRIOL, signified a shiny crystalline body. The top of the design shows the conjunction of Sol and Luna (sophic sulphur and sophic mercury), under the astrological influence of the planets Mars, Saturn, Mercury, Jupiter, and

Fig. 13. The Vitriol Acrostic

Venus, shown in that order. The saturnine symbol is darkened (p. 68), and the symbol of Mercury supports a cup or chalice, which may possibly be likened to the Holy Grail, a medieval symbol of physical and spiritual life.

The mercurial symbol rests in turn upon an orb, representing the Stone. The five-pointed star beneath this is suggestive of the five metals, corresponding to the planets above. On the left, these metals are shown as originating from the two 'seeds' (sophic sulphur and sophic mercury) of the enclosing circles. The hoops on the right may perhaps refer to the Ouroboros, or tail-eating serpent, (p. 25), the symbol of rejuvenation and of eternity. The lion and two-headed eagle signify the fixed and volatile principles; pointing fingers are reminiscent of moon talismans, but the outstretched fingers may mean a benediction; and the outside square may symbolise the four elements. The ornaments in the four corners are adventitious additions. Such representations, although they might appear as haphazard jumbles to the layman, conveyed a wealth of meaning to the initiated 'Sons of Hermes.'

Alchemical literature abounds in enigmatical representations of this general type. Some of them were very complex. They were often furnished with dark and unhelpful allusions, as for example in Basil Valentine's *Twelve Keys*. Libavius, somewhat more relenting in his *Alchymia* (1606), went so far as to give a systematic lettered description of several remarkable designs, the simplest of which is reproduced in Fig. 14. Here, (A) is 'a double-bodied lion with one head, whereby is signified the first matter of the Stone. . . . (B) Lions on both sides, as if on the stair of Solomon, five in all, to signify five metals from one root. . . . These can pass into Sun and Moon. . . . (C) A picture of the Sun. (D) A picture of the Moon. (E) A bath, in which sits a King with a Queen. This is also the type of the marriage-bed, for the procreation of their kind. Also a garden with a tree in it, bearing the apples of the Hesperides. (F) A King with a crown and sceptre decorated with lilies. . . . (G) In the middle, a tree bears golden fruits, while golden stars surround crowns, to signify multiplication and increase, or else the fruit of projection.'

In brief, the shedding of their garments by King and

Fig. 15. The Figures of Abraham (See p. 49)

Fig. 17. The First Key of Basil Valentine

(*See p. 56*)

Queen symbolises the elimination of impurities from the primitive materials in preparing the proximate ones; and the Bath or Fountain of the Philosophers is an image of the menstruum in which the resulting sophic sulphur and sophic mercury are conjoined.

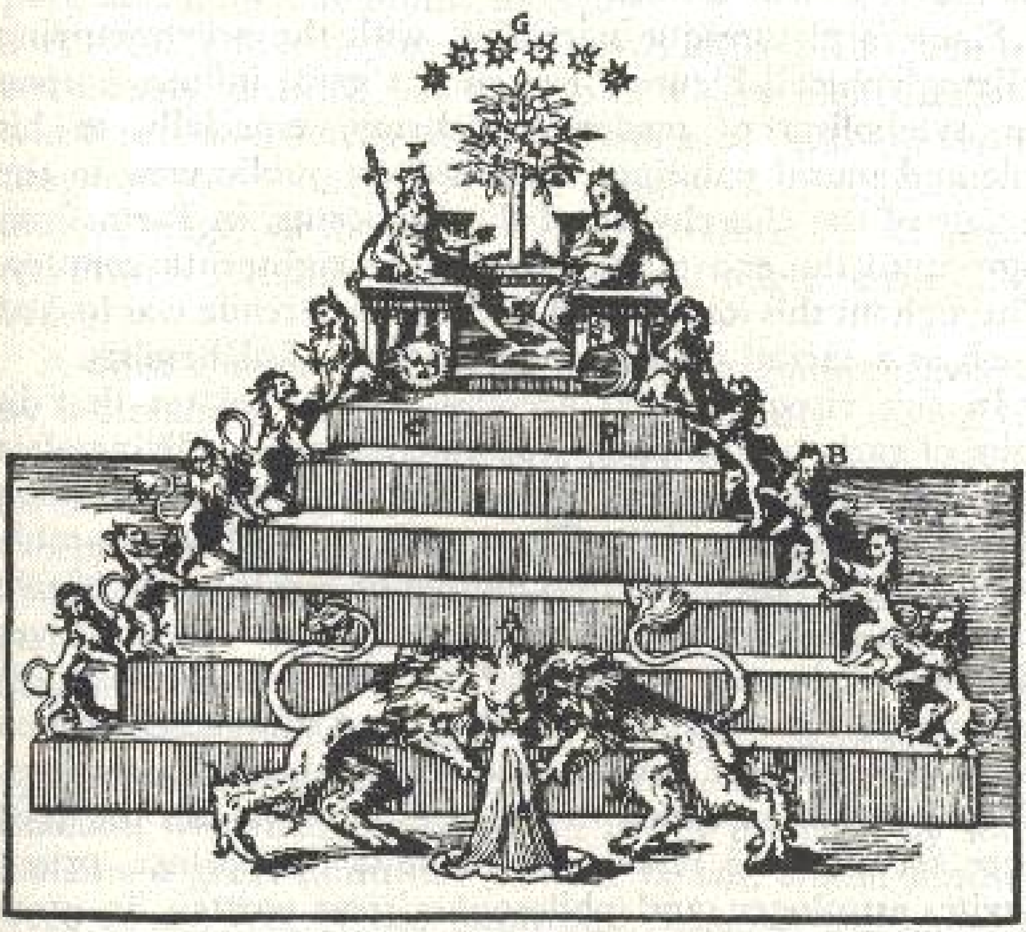


Fig. 14. The Bath of the Philosophers

The Figures of Abraham

Of outstanding and compelling interest in the vast literature of medieval alchemy is a short work ascribed to Nicholas Flamel, a Parisian scrivener who is said to have lived from 1330 to 1418, and to have acquired great wealth. This writing was first published in English in 1624, in the form of a modest little book of 139 small pages, now extremely rare. It is entitled: 'Nicholas Flammel, His

Exposition of the Hieroglyphicall Figures which he caused to bee painted upon an Arch in *St. Innocents Churchyard*, in Paris. *Faithfully, and* (*as the Maiesty of the thing* requireth) religiously done into English out *of the French and Latine Copies*. . . . Imprinted at *London* by *T.S.* for *Thomas Walkley*, and are to bee solde at his Shop, at the Eagle and Childe in *Britans Bursse*. 1624.'

Flamel's picturesque narrative, with the accompanying 'Hieroglyphicall Figures,' exercised a great influence upon the symbolism of medieval alchemy, especially as his coloured mural paintings remained on public view in the arcade of the churchyard of the Innocents, in Paris, from 1407 until the end of alchemy in the eighteenth century. Throughout this long period, indeed, the arcade was looked upon as a sacred shrine by generations of alchemists.

In this circumstantial account Flamel relates that in spite of early hardships he was able to earn his living after the death of his parents 'by making Inventories, dressing accounts,' and the like. Then, without further preamble he states that 'there fell into my hands, for the sum of two Florens, a guilded Booke, very old and large . . . the cover of it was of brasse, well bound, all engraven with letters, or strange figures.' The writing was supplemented, on every seventh leaf, by a series of symbolical paintings. These were often called the Figures of Abraham the Jew, since according to Flamel the name of this 'prince, priest, Levite, astrologer, and philosopher' was written 'in great Capitall Letters of gold' upon the first leaf of the book.

The paintings were 'full of faire figures *enlightened* . . . for the worke was very exquisite.' Among them was one of 'a *yong man*, with wings at his anckles, having in his hand a *Caducaean* rodde, writhen about with two *Serpents* . . . against him there came running and flying with open wings, a great old man, who upon his head had an *houre-glasse* fastened, and in his hands a hooke (or sithe) like *Death*, with the which, in terrible and furious manner, hee would have cut off the feet of *Mercury*.'

This emblem (Fig. **15**, I) signifies the cupellation of argentiferous lead, whereby the impurities sink into the porous cupel and the 'fixed' pure essence of silver, otherwise sophic mercury, is left. Saturn, or Kronos, identified with lead, has cut off the feet of the impure form of 'mercury' (silver) contained in the argentiferous lead, thereby yielding pure and immobile sophic mercury.

Another emblem (Fig. **15**, II) shows a tree with white and red flowers, growing 'on the top of a very high *mountaine*, which was sore shaken with the *North wind*,' and infested by dragons (sophic mercury) and griffins (a combination of lion and eagle, or fixed and volatile). Here, the white and red flowers stand for the white and red stages of the Great Work.

A third emblem (Fig. **15**, III) depicts a garden traversed by a stream of white water, running rapidly 'among the hands of infinite people, which digged in the Earth seeking for it; but because they were blinde, none of them knew it, except here and there one which considered the *weight*.' This was the Hermetic Stream, often described by the alchemists as 'heavy water,' or 'water not wetting the hands.'

By far the most famous of the Figures of Abraham (Fig. **15**, IV), consisted of a painting of 'a *King* with a great *Fauchion*, who made to be killed in his presence by some *Souldiers* a great multitude of little *Infants*, whose Mothers wept at the feet of the unpittifull *Souldiers*: the bloud of which *Infants* was afterwards by other Souldiers gathered up, and put in a great vessell, wherein the *Sunne* and the *Moone* came to bathe themselves.'

To this description, Flamel added: 'And because that this History did represent the more part of that of the *Innocents* slaine by Herod . . . I placed in their *Churchyard* these *Hieroglyphick Symbols* of this secret science.'

Flamel also describes, with close attention to vestments and colours, the central figure of the Saviour, flanked by those of St. Paul and St. Peter, with Flamel and his wife, Perrenelle, kneeling beside them. The significance of colour is emphasised in the statement: 'I have also set against the wall, on the one and the other side, a *Procession*, in which are represented by order all the colours of the *stone*, so as they come and goe, with this writing in French:

> *Moult plaist a Dieu procession,*
> *S'elle est faicte en devotion:*

that is,

> *Much pleaseth God procession,*
> *If't be done in devotion.*'

The imagery of these extensive mural paintings was therefore of mingled alchemical and religious significance. In one respect the central allegory of the Massacre of the Innocents, represented in this dual manner and proclaimed so publicly, was unfortunate; for it brought some disrepute to the alchemists by suggesting that possibly they had a professional interest in the blood of infants. In actual fact, of course, this alchemical use of the poignant biblical story was merely one among numerous renderings, including for instance that of Libavius (Fig. 14), depicting the Bath of the Philosophers. Flamel himself was troubled about this emblem until he had studied 'the Bookes of the *Philosophers*, and in them learned their so hidden secrets,' with the interpretation of infants' blood as the mineral spirit of metals, 'principally in the *Sunne*, *Moone*, and *Mercury*.' The cryptic language of the 'guilded Booke' was indeed the cause, 'that during the space of *one and twenty yeeres*, I tryed a thousand broulleryes [misconceptions], yet never with *bloud*, for that was wicked and villanous.'

An Alchemical Epic

Flamel succeeded at length in solving the mysteries of the 'guilded Booke' by entering upon a lengthy and romantic pilgrimage, which ranks high among the epics of alchemy. His abortive studies of the writings and emblems, he says, 'made me very heavy and sollitary, and caused me to fetch many a sigh. My wife *Perrenelle*, whom I loved as my selfe, and had lately married, was much astonished at this. . . . I could not possibly hold my tongue, but told her all . . . whereof . . . she became as much enamored as my selfe.'

Having sought illumination in vain from 'the greatest Clerkes in *Paris*,' he set off upon a pilgrimage to Spain, with the full consent of his beloved Perrenelle, taking with him copies of the enigmatic Figures of Abraham. In that ancient land, into which alchemy had been brought by the Muslims, he hoped to discover an informed adept, possibly in the guise of a Jewish priest steeped in cabbalistic and alchemic lore. And so, assuming the pilgrim's garb and staff, Flamel, as he says, 'put my selfe upon my way; and so much I did, that I arrived at *Montioy*, and afterwards at *Saint Iames* [of Galicia], where with great devotion I accomplished my vow.'

This done, he made the acquaintance, at Leon, of a Jewish physician, 'who was very skilfull in sublime Sciences, called Master *Canches*. As soon as I had showen him the figures of my *Extraict*, hee being ravished with great astonishment and ioy, demanded of me incontinently, if I could tell him any newes of the *Booke*, from whence they were drawne? I answered him in *Latine* (wherein hee asked me the question).' The reply threw Master Canches into such 'great Ardor and ioy' that he agreed to return to France with Flamel, leaving from Santander by the Biscay passage.

'Our voyage had been fortunate enough, and all ready,' continues Flamel, 'he had most truly interpreted unto mee the greatest part of my figures, where even unto the very points and prickes, he found great *misteries*, which seemed unto mee most wonderful, when arriving at *Orleans*, this learned man fell extreamely sicke, being afflicted with excessive vomitings, which remained still with him of those he had suffered at Sea. . . . In summe hee dyed . . . by reason whereof I was much grieved, yet as well as I could, I caused him to be buried in the *Church* of the holy *Crosse* at *Orleans*.'

It was therefore a sad return for the weary pilgrim of alchemy until at last he reached Paris and came into sight of the modest little house with the sign of the Fleur-de-Lys, where the rue des Écrivains runs into the rue de Marivaus. 'He that would see the manner of my arrivall, and the ioy of *Perenelle*, let him looke upon us two, in this *City* of *Paris*, upon the doore of the *Chappell* of *St. Iames* of the *Bouchery*, close by the one side of my *house*, where wee are both painted, my selfe giving thanks at the feet of *Saint Iames of Gallicia*, and *Perrenelle* at the feet of *St. Iohn*, whom shee had so often called upon.'

Flamel's conversations with the lamented Master Canches had given him some knowledge of 'the first *Principles*, yet not their first *preparation*, which is a thing most difficult, above all the things in the world: But in the end I had that also, after long errours of *three yeeres*, or thereabouts; during which time I did nothing but study and labour. . . . Finally, I found that which I desired, which I also soone knew by the strong *sent* and *odour* thereof. Having this, I easily accomplished the *Mastery*, for knowing the *preparation* of the first *Agents*, and after following my Booke according to the *letter*, I could not have missed it, though I would.'

Now comes the most remarkable part of Flamel's story, clothed in a wealth of circumstantial detail: 'Then the first time that I made *proiection*,' he resumes, 'was upon *Mercurie*, whereof I turned halfe a pound, or thereabouts, into pure *Silver*, better than that of the *Mine*, as I my selfe assayed, and made others assay many times. This was upon a Munday, the 17. of *January* about noone, in my house, Perrenelle onely being present; in the yeere of the restoring of mankind, 1382. And afterwards, following alwayes my Booke, from word to word, I made *proiection* of the *Red stone* upon the like quantity of *Mercurie*, in the presence likewise of *Perrenelle* onely, in the same house, the *five and twentieth day* of *Aprill* following, the same yeere, about five a *clocke* in the *Evening*; which I transmuted truely into almost as much pure *Gold*, better assuredly than common *Golde*, more soft, and more plyable. I may speake it with truth, I have made it three times, with the helpe of *Perrenelle*, who understood it as well as I, because she helped mee in my operations, and without doubt, if she would have enterprised to have done it alone, shee had attained to the end and perfection thereof. I had indeed enough when I had once done it, but I found exceeding great pleasure and delight, in seeing and contemplating the *Admirable workes of Nature*, within the *Vessels*.'

Flamel's story gives one of the earliest and most graphic accounts of an alleged transmutation; to it, indeed, has sometimes been ascribed that frantic search for the Philosopher's Stone which certain writers have termed the mania of the fifteenth century. Flamel's narrative ends with a detailed account of the numerous benefactions which he and Perrenelle had made to the city of Paris at the time when he 'wrote this *Commentarie*, in the yeere *one thousand foure hundred and thirteene*.'

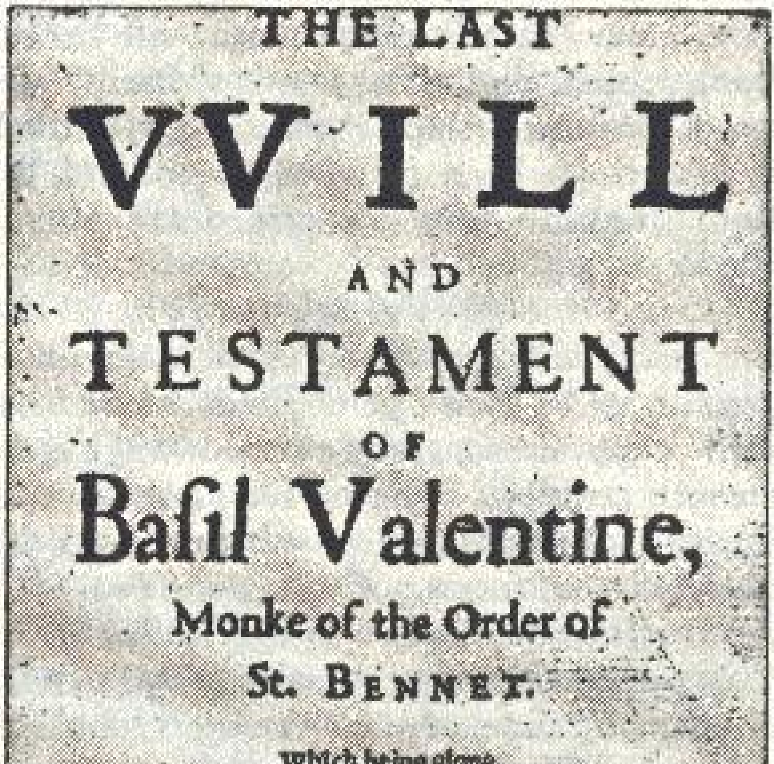
Later ages have rejected the ascription of Flamel's wealth to alchemical gold, and doubts have been cast upon the authenticity of the picturesque narrative written under his name. Even that name has fallen under suspicion as being too apt for an alchemist; but it must be remembered that the assumption of impressive names was a recognised alchemical practice. That such a person existed cannot be doubted. There can still be seen in the Musée de Cluny, in Paris, a contemporary marble tablet from the former church of St. Jacques-la-Boucherie, inscribed with his name and a record of his benefactions, together with insculped figures of the Saviour, St. Peter and St. Paul, and interspersed symbols of the sun and moon. As a pendant to this romantic story of Flamel, the tablet disappeared when the church was demolished in 1797, to be recovered many years afterwards from the shop of a greengrocer and herbalist in the rue des Arcis, where its smooth marble back had served as an admirable chopping block for the proprietor's cooked herbs. *Sic transit gloria mundi!* Another tangible relic of Flamel may be found in fragmentary remains of his house of 1407, still visible in the fabric of No. 51 in the rue de Montmorency.

'Flamel!' exclaimed Victor Hugo's alchemist. 'There's predestination in the very name! *Flamma!* yes, fire—that is all. The diamond exists already in the charcoal, gold in fire!'

The 'Mighty King' of Alchemy

Some two centuries after the days of Nicholas Flamel there appeared under the name of Basil Valentine a series of writings of unsurpassed fame in the annals of alchemy. These writings have a twofold character: they are mainly mystical and enigmatic; but sometimes they contain details of practical chemical operations almost as intelligible as those of a modern text-book of chemistry. The identity of the writer, is, in itself, one of the unsolved enigmas of alchemy. The name Basil Valentine, signifying 'mighty king,' or 'valiant king,' conforms to the best traditions of alchemical pseudepigraphy, according to which various writings were endowed with authority by false ascriptions to famous persons of bygone times or to mysterious 'veiled masters' with high-sounding names.

According to the alchemical tradition, Basilius was a monk belonging to the Benedictine fraternity of St. Peter of Erfurt in the latter half of the fifteenth century. Indeed, a German book published in 1645, and later translated into English (Fig. 16), was entitled 'The Last Will and Testament of Basil Valentine, Monke of the Order of St. Bennet. Which being alone, He hid under a Table of Marble, behind the High-Altar of the Cathedral Church, in the Imperial City of *Erford*: leaving it there to be found by him, whom Gods Providence should make worthy of it.' A later writer stated solemnly that the revelation came in the



THE LAST

VVILL

AND

TESTAMENT

OF

Basil Valentine,

Monke of the Order of

St. BENNET.

Which being alone,
He hid under a Table of Marble, behind the High-Altar of the Cathedral Church, in the Imperial City of *Erford*; leaving it there to be found by him, whom Gods Providence should make worthy of it.

To which is added

TWO TREATISES

The First declaring his Manual Operations.
The Second shewing things Natural and Supernatural.

Never before Published in *English*.

LONDON,
Printed by *S. G.* and *B. G.* for *Edward Brewster*, and are to be sold at the sign of the *Crane* in St. *Pauls Church-yard*, 1671.

Fig. 16. Title-page of
The Last Will and Testament of Basil Valentine

fullness of time through a thunderbolt striking the church!

In actual fact, some of the chemical knowledge recorded in the intelligible parts of these writings would be antedated by a century if ascribed to the fifteenth century; and the first book printed under the name of Basil Valentine is dated 1599. The authorship of some, or all, of the Basilian works has sometimes been assigned to Johann Thölde, a salt-maker of Frankenhausen, who issued a number of them.

The Twelve Keys of Basilius

Of the mystical writings bearing Basil Valentine's name, pride of place is taken by the celebrated *Twelve Keys*, which appeared in many editions and several languages during the seventeenth century. The twelve illustrative emblems achieved great popularity and were reproduced time after time in many varietal forms. Each of the twelve emblems was provided with an allegorical description or 'explanation.' The complete series purported to open the door 'to the most Ancient Stone of our Ancestors, and the most Secret Fountain of Health.'

The First Key (Fig. 17) symbolises to the adept the preparation of the proximate materials of the Great Work. 'Take a fierce grey Wolf,' runs the direction. 'Cast to him the body of the King, and when he has devoured it, burn him entirely to ashes in a great fire. By this process the King will be liberated; and when it has been performed thrice the Lion has overcome the Wolf, who will find nothing more to devour in him. Thus our Body has been rendered fit for the first stage of our work.' Here, the grey wolf is alchemical antimony (antimony sulphide, or stibnite), known also as *lupus metallorum*, or 'wolf of the metals,' because of its capacity to unite with all the alchemical metals except gold. The repeated fusion of gold in this way, shown in the emblem of the First Key by a wolf leaping over a heated crucible, was therefore justifiably used as a purifying process for this noble metal. Also, silver, represented by the Queen, was purified by heating it with lead in a cupel. The wooden-legged old man (not to be confused with Hephaestus, p. 36), carrying a scythe, is Saturn, or Kronos, identical with Flamel's 'great old man' with the hour-glass and scythe (p. 48), who was likewise engaged in the same process of cupelling argentiferous lead and thus arriving at sophic mercury, as here shown in the emblem of the First Key.

The union of the resulting sophic sulphur and sophic mercury in the Hermetic Vase, leading to the Stone, is symbolised by the marriage of King and Queen: 'the faire White Woman married to the Ruddy Man,' in the language of Norton's *Ordinall*. The Queen's three flowers signify either the *tria prima* or the triple purification of the King; and her fan of peacock's feathers is also symbolic (p. 38).

All of the twelve emblems of Basilius are well calculated to arrest the attention, and the accompanying descriptions contain a wealth of grandiloquent and inflated verbiage. 'Let me tell you allegorically,' writes the pontifical Basilius of his Ninth Key, 'that you must put into the heavenly Balance the Ram, Bull, Cancer, Scorpion, and Goat. In the other scale of the Balance you must place the Twins, the Archer, the Water-bearer, and the Virgin. Then let the Lion jump into the Virgin's lap, which will cause the other scale to kick the beam. Thereupon, let the signs of the Zodiac enter into opposition to the Pleiads, and when all the colours of the world have shown themselves, let there be a conjunction and union between the greatest and the smallest, and the smallest and the greatest.'

Even Basilius must have felt that he had transcended himself in this imaginative flight, for he added, condescendingly: 'This will seem unintelligible to many, and it certainly does make an extraordinary demand upon the mental faculties.' The adept, however, was obliged to wrap himself in a mantle of obscurity, 'because the substance is within the reach of everyone, and there is no other way of keeping up the divinely ordained difference between rich and poor.'

V · STRANDS IN THE ALCHEMICAL WEB

SOME of the numerous strands of the complicated warp and woof of alchemical doctrine, tenet, and lore can be seen at a glance, although not in their full significance. There are many others that reveal themselves only to a deeper view. Some of the strands, at a proper stage in the study of alchemy, call for more than a superficial examination: of these, a few should be mentioned at this point.

Religion

First of all, there is the religious element. The 'divine Art' of alchemy, owning among its remote ancestors the Sun-god and Moon-goddess of the primitive civilisations, and nurtured perhaps in the temples of ancient Egypt and China, has always been closely bound up with the beliefs and observances of religion. In the early centuries of the Christian era, when alchemy began to take definite shape, contributions of this kind came alike from Christians, Jews, Gnostics, and neo-Platonists. Still others came as an inheritance from a more remote epoch.

For example, in Flamel's Figures of Abraham (Fig. 15), the greatest prominence is given to symbols illustrative of the fundamental beliefs of Christianity; but apart from this, in the seven numbered paintings, there is a remarkable recurrence of the symbol of the serpent. Flamel's description of the 'Hieroglyphicall Figures' includes references to 'a *Virgin* and *Serpents* swallowing her up' . . . 'a *Crosse* where a *Serpent* was crucified' . . . and 'many faire fountains, from whence there issued out a number of *Serpents*, which ran up and downe here and there.'

The serpent, also shown as a snake or dragon, was indeed one of the commonest of alchemical symbols. It had many interpretations. The Ouroboros, or tail-eating serpent of ancient Egypt, going back some sixteen centuries before the Christian era, symbolised regeneration, eternity, or the universe; also it embodied the later Platonic idea of the unity of matter, the 'all is one' (Fig. 7). These interpretations were taken over by the alchemists, who also used serpentine symbols for the fixed and volatile principles, masculine and feminine characters, sophic sulphur and sophic mercury, the *tria prima,* and in a wider sense to denote wisdom, power, and creative energy.

It is fairly certain that the symbol of the serpent came down into alchemy from primitive religions based upon sun-worship, serpent-worship, and phallism. In ancient Babylonia the serpent was held in sacred veneration as the symbol of the sun-god; indeed, it has been said that in the ancient world the serpent 'entered into the mythology of every nation, consecrated almost every temple, symbolised almost every deity, was imagined in the heavens, stamped on the earth, and ruled in the realms of everlasting sorrow.'

Since so many of the medieval adepts of alchemy were men whose lives were subject to deep religious convictions, it is not surprising to find that alchemical writings of their era were imbued with the beliefs and doctrines of Christianity. There was, indeed, a close connection between alchemical tenets and certain religious doctrines, including the Redemption and the Resurrection. In particular, the alchemists were wont to liken the Christian mystery of the triune Godhead to the alchemical mystery of a triune Stone. George Ripley, canon of Bridlington, prefaced his *Compound of Alchymie* with the prayer: 'O Unity in the substance, and Trinity in the Godhead. . . . As Thou didst make all things out of *one* chaos, so let me be skilled to evolve our microcosm out of *one* substance in its three aspects of Magnesia, Sulphur, and Mercury.' The same conception of the Stone as a triune microcosm recurs in some 'Verses Belonging to *an Emblematicall* Scrowle: *supposed to be invented* *by* Geo: Ripley,' and contained in Elias Ashmole's *Theatrum Chemicum Britannicum*, published at London in 1652:

> Thou must part him in three,
> And then knit him as the Trinity:
> And make them all but one,
> Loe here is the *Philosophers Stone.*

In the same fascinating collection of 'Severall Poeticall Pieces of our Famous *English Philosophers*, who have written the *Hermetique Mysteries* in their owne Ancient Language,' Ashmole records a medieval English poem relating how the blessed Stone 'Fro Heven wase sende downe to *Solomon.*' The poet likens its constituents to the three gifts of the Magi at Bethlehem:

> Aurum [gold] betokeneth heer, owre Bodi than,
> The wych was brought to God and Man.
> And Tus [frankincense] alleso owre Soul of lyfe,
> Wyth Myrham [myrrh] owre Mercury that ys hys Wyfe.
>
> Here be the thre namys fayre and good
> And alle thaye ben but one in mode.
> Lyke as the Trinite is but on,
> Ryght so conclude the *Phylosofeers Stone.*

The same conception is repeated in the later writings of Basil Valentine. Moreover, a writer in *Gloria Mundi* expounds a related conception in which the Stone is likened to the biblical 'stone which the builders rejected': 'The Stone is cast away and rejected by all. Indeed it is the Stone which the builders of Solomon disallowed. But if it be prepared in the right way, it is a pearl without price, and, indeed, the earthly antitype of Christ, the heavenly Corner Stone. As Christ was despised and rejected in this world by the Jews, and nevertheless was more precious than heaven and earth; so it is with our Stone among earthly things.'

A further close relationship between alchemy and religion is to be found in the common association of the alchemists and alchemical emblems with ecclesiastical buildings. Thus, Nicholas Flamel (p. 48) recorded and exposed the Figures of Abraham in the form of coloured mural paintings in the arcade of the churchyard of the Innocents, in Paris. Ashmole mentions the existence, in 1652, of an alchemical painting upon a wall of Westminster Abbey, and describes in detail an alchemical window, symbolising in colour the preparation of the Stone, which formerly existed in St. Margaret's Church, Westminster. Moreover, Ripley long before this had alluded to '*Westminster* Church, To whych these *Phylosophers* do haunte.' Similarly, Notre Dame at Paris was once a resort of alchemists, and some of the sculptured ornamentations of this beautiful Gothic cathedral bore an alchemical significance.

Again, as Nicholas Flamel wrote, in his description of the Figures of Abraham, alchemical symbols 'may represent *two things*, according to the capacity and understanding of them that behold them: First, the mysteries of our future and undoubted *Resurrection*, at the day of Iudgement, and comming of good *Iesus*, (whom may it please to have mercy upon us) a Historie which is well agreeing to a *Churchyard*. And secondly, they may signifie to them, which are skilled in Naturall *Philosophy*, all the principall and necessary operations of the *Maistery*.'

The spiritual interpretation of alchemy, in terms of psychology and mystical theology, has sometimes been carried to great lengths. As an example, in the processes within the Hermetic Vase, the black stage has been likened to 'the dark night of the soul,' the white to 'the morning light of a new intelligence,' and the red to 'the contemplative life of love.'

Mythology

The imagery of alchemy was closely bound up with mythological conceptions. In particular, it was related to the supposed characteristics of gods and other supernatural beings, notably those of the pantheons of Egypt, Greece, and Rome. Hermes Trismegistos, the patron of alchemy and alleged father of the Hermetic Art, was the Greek equivalent of the Egyptian god, Thoth, the personification of wisdom. The Egyptian triad, Osiris, Isis, and Horus, were all endowed with alchemical attributes. Osiris, the Sun-god, was a symbol of the active, masculine principle and vivifying force; Isis, the Moon-goddess, passive and fertile, bore an earthly significance; Horus, their annual offspring, was an image of the infant year and the process of growth or multiplication. Some of the alchemical associations of Greek deities and their Roman analogues, in particular their supposed connection with planets and metals, have already been mentioned. Among other members of these pantheons, Hephaestus, or Vulcan, presided over the activities of 'labourers in the fire' and other alchemical craftsmen; and Pallas Athene, or Minerva, was held in high esteem by the alchemists as the forceful goddess of wisdom.

The alchemical craving for obscure expression found an almost inexhaustible fount of allegorical material in the prolific realm of classical mythology. Among the more general conceptions the operations of the Great Work were often likened to the tasks of Hercules; Ulysses, the great wanderer, was the adept who 'errs in divers ways until he reaches the desired goal'; the fruitless efforts of Penelope, who unwove by night that which she had woven by day, were viewed as an image of the abortive labours of the uninformed seekers after the Stone, as were also the vain struggles of Sisyphus. In the neatly ironical words of Ben Jonson:

> Was not all the knowledge
> Of the Egyptians writ in mystic symbols?
> Speak not the Scriptures oft in parables?
> Are not the choicest fables of the poets,

Fig. 18. Melencolia

(*See p. 67*)

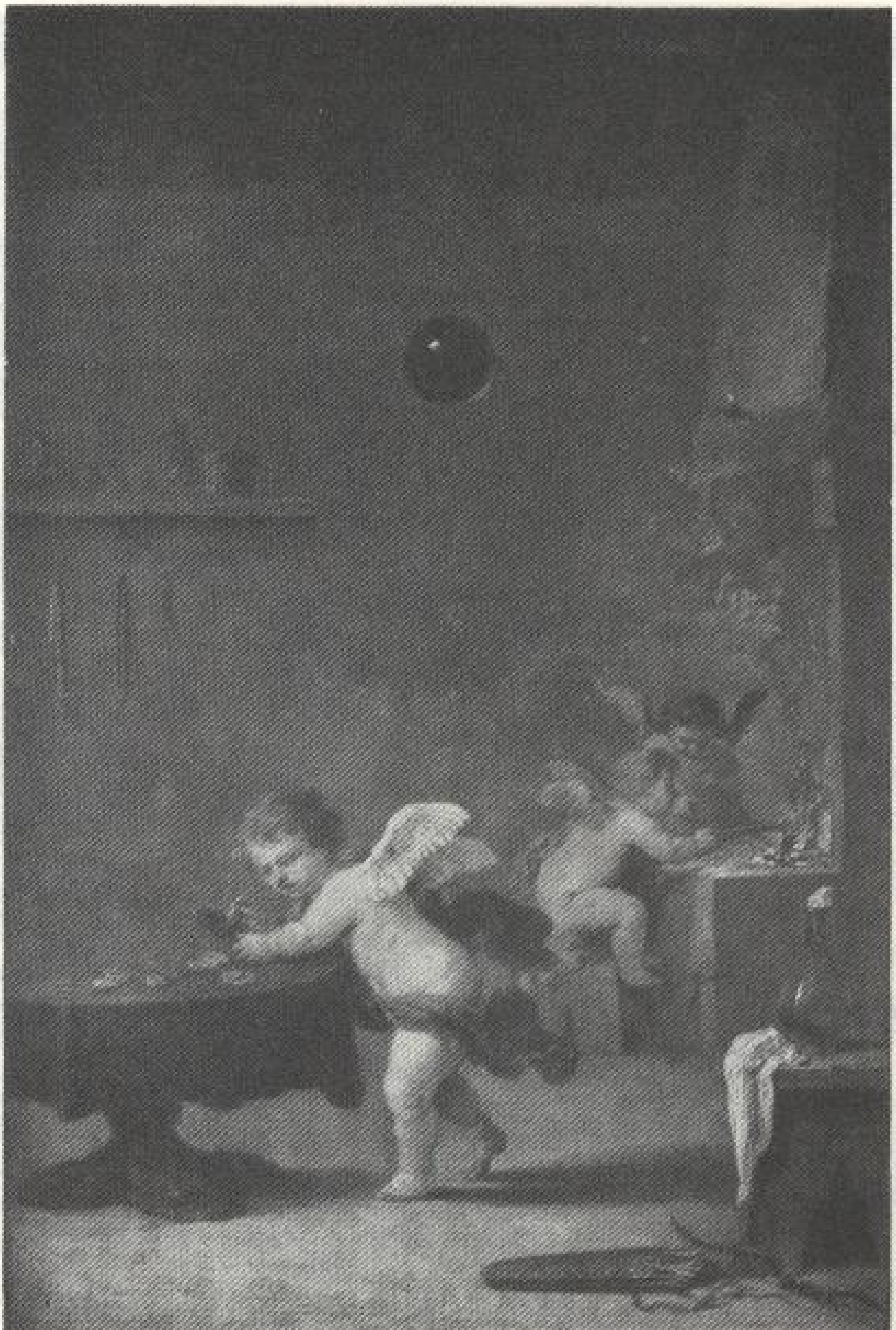


Fig. 19. Cupids in the Laboratory (*Ludus puerorum*)
(*See p. 67*)

That were the fountains and first springs of wisdom,
Wrapped in perplexed allegories?

I urged that,
And cleared to him that Sisyphus was damned
To roll the ceaseless stone, only because
He would have made ours common.

Some alchemists supposed that the Golden Fleece of the Argonauts was a papyrus inscribed with the secret of transmutation. An alchemical poem quoted by Ashmole refers to Apollo slaying the Python, also to the hollow oak of Cadmus, and to Jason's 'Fiery steeres.' Apollo and the terrorising Python of Juno (p. 22) are here sophic sulphur and sophic mercury; Cadmus pinning the serpent with his lance to the hollow oak is the adept fixing mercury with fire in the athanor, or Furnace of the Sages; and Jason controlling the fiery bulls is Norton's 'parfet *Master* . . . which knoweth his Heates high and low' (p. 84). These and other burgeonings of alchemical imagery come to a luxuriant flowering in *The Alchemist*, where the incomparable Ben Jonson gives one glittering display after another of his unsurpassed and eloquent command of the recondite language and imagery of alchemy:

The bulls, our furnace,
Still breathing fire: our argent-vive, the dragon:
The dragon's teeth, mercury sublimate,
That keeps the whiteness, hardness, and the biting:
And they are gathered into Jason's helm,
(The alembic), and then sowed in Mars his field,
And thence sublimed so often, till they're fixed.
Both this, th' Hesperian garden, Cadmus' story,
Jove's shower, the boon of Midas, Argus' eyes,
Boccace his Demogorgon, thousands more,
All abstract riddles of our stone.

Curiously enough, this application of classical mythology to alchemy reached its zenith in the early seventeenth century, when 'the Divine Art' was beginning to decline, and was even sustained, in a fashion, until the second half of the eighteenth century. Up to the fifteenth century, alchemical writers had not used mythological fables to any great extent as a concealing medium for their secrets and processes. Later writers, in particular Count Michael Maier early in the seventeenth century, developed an impressive system of Hermetic mythology, which reached its zenith more than a century afterwards in the writings of Pernety, at a time when alchemy had become almost universally discredited. In his remarkable *Dictionnaire Mytho-Hermétique*, published at Paris in 1758, and in other writings, this credulous 'Religieux Bénédictin', imbued with a mass of undigested learning, maintained that Hermes had devised the mythological systems of ancient Egypt and Greece for the express purpose of enabling the secrets of alchemy to be handed down from one generation to another of alchemical adepts in the form of enigmas, parables, allegories, fables, and hieroglyphics.

The application of classical mythology to alchemy had found a much earlier and more temperate expression in the works of Michael Maier, particularly in an attractive and intriguing book entitled *Atalanta Fugiens*. This Michael Maier (1568-1622) was a very remarkable man, so versatile as to enable him to take rank not only as an alchemist, but also as a philosopher, physician, classical scholar, and musician. He became physician and private secretary to the Emperor Rudolph II at Prague, and at the same time acted as one of his alchemical consultants. At that time Prague was a famous alchemical centre; the Zlatá ulička, or 'Golden Lane,' was a nest of alchemists, whose habitations may still be seen there.[1] Rudolph himself had so great an enthusiasm for alchemy that he was called 'the German Hermes.' Maier was an omnivorous reader who developed into a prolific writer on mystical and allegorical alchemy. His erudition was profound, but his writings

[1] *Humour and Humanism in Chemistry*, Fig. 89.

were diffuse, obscure, and completely uncritical. He was so incredibly credulous that he fathered innumerable mare's-nests and even feathered some of them. Nevertheless, his 'ruinous follies,' as they have been called, seem to have impressed the Emperor, who made him a Pfalzgraf, or Count Palatine.

At the present day Maier's works are valued chiefly because of their striking and artistic copper-engravings, executed by Johannes Theodorus de Bry at Frankfurt-on-Main. The most attractive and interesting of Maier's books, *Atalanta Fugiens* (1618), contains a handsome title-page by this artist, together with fifty engravings of alchemical emblems, which draw largely upon alchemical mythology for their subjects.

The title of this work, 'Atalanta Fleeing,' suggests an analogy between the pursuit of the fleeing Atalanta and that of the elusive Stone. According to the fable, Atalanta, the fleetest-footed of mortals, refused to accept the advances of any suitor who failed to outstrip her in a race: but, of course, *ex hypothesi* she always came in first; until the envious Aphrodite (Venus) loaded the dice against her by giving Hippomenes three golden apples to throw into the path of this fastest of maidens as she ran. The sequel has been ably summarised by the poet who wrote:

> The nimble Virgin, dazled to behold
> The glittering apple tumbling o'er the mold,
> Stop'd her career to seize the rowling gold.

The rest was easy for Hippomenes. This contest, with concomitant incidents, is shown in the handsome design on the title-page of the book.

The fifty engravings of *Atalanta Fugiens* make use of many mythological themes and fancies. A great variety of other alchemical imagery includes representations of the Philosopher's Egg (Fig. **10**) and the ubiquity of the Stone

(p. 30), already mentioned. The first two emblems in the series bear titles taken from the Emerald Table, and referring to the Philosopher's Stone: 'The wind has carried him in its belly'; 'The earth is his nurse.' In the latter design the earth is represented by a grotesque female figure suckling an infant; and at her feet are shown a she-wolf and a she-goat affording similar nourishment to their respective foster-children, Romulus and Remus, and Jupiter. Each of the fifty engravings bears a Latin epigram written in elegiac couplets, and an allusive title, together with a discourse in the text. The epigram of the second engraving begins: 'We are told that Romulus sucked a she-wolf's shaggy udders, but Jupiter a she-goat's, and that the tale is true.'

The Saturnine Mysticism

In the twelfth emblem of *Atalanta Fugiens*, 'old Father Time' makes another of his frequent appearances in alchemical iconography (cf. Figs. **15**, **17**). Maier's emblem illustrates an untoward incident in the fable of Kronos (Saturn), who was addicted to swallowing his own offspring. Fortunately for the Greek pantheon, Zeus (Jupiter) escaped this fate, owing to the forethought of his mother. Rhea, warned by earlier happenings, hit upon the device of wrapping a stone in swaddling clothes and leaving it in the cot, from which it was abstracted as soon as her back was turned by the expectant Saturn, who swallowed it with misplaced gusto. This indigestible morsel was naturally seized upon by the mystical alchemists as the Philosopher's Stone. Maier's epigram runs: 'Wouldst thou know the reason why so many poets tell of Helicon, and why its summit is the goal of each one? There is a Stone placed on the topmost height, a memorial, which his father swallowed and spewed up instead of Jupiter. If thou understand the matter just as the words sound [literally] thy mind is unskilful, for that Stone of Saturn's is the Chymists' Stone.'

This emblem of Michael Maier forms one of the unnumbered expressions of that Saturnine mysticism which permeates the whole corpus of alchemical doctrine and literature. The most striking of all pictorial illustrations of that mysticism had been given a hundred years earlier by one who was not an alchemist, namely, by the great German artist, Dürer, in that masterpiece of copper-engraving (Fig. **18**) which he entitled 'Melencolia' (1514). Designed perhaps as the first of four projected engravings to illustrate the four temperaments, this composition is replete with alchemical significance. The polyhedral Stone of Saturn, the crucible, the sharp implements and tools, the seven-runged ladder, the watery background, and the rainbow are all familiar alchemical symbols. The central, brooding figure, 'with a sad leaden downward cast,' is a personification not only of melancholy, but also of the baffled seeker of the Stone, or, in more general terms, of the student and seeker after wisdom.

The doctrine of melancholy is inseparably bound up with the Saturnine mysticism of alchemy, and this association finds many expressions in Dürer's composition. Measurement, an important element of mysticism, is typified by the compasses, balance, and hour-glass, the last-named being a particular symbol of time and of Kronos. The infant recalls Saturn's unorthodox diet; the grindstone upon which he sits conveys the same idea of regeneration and continuity as does the time-worn symbol of the tail-eating serpent (Fig. **7**).

A little later than Dürer's engraving of 1514 came three symbolic paintings of Melancholy by Cranach. All of these show infants at play, some with a hoop, others with a sphere, corresponding to Dürer's grindstone. Moreover, one of Teniers' paintings (Fig. **19**), executed more than a century later, was based upon this so-called *ludus puerorum*, or 'child's play' motive in alchemy: in it, the infants are shown as winged cupids engaged at play in an alchemical laboratory, and above them hovers in the air a thin and shining sphere or bubble, corresponding to the sphere, hoop, or grindstone of Dürer and Cranach.

Usually the Saturnine mysticism is associated with humidity or wetness, and sometimes with the *opus mulierum*, or 'labour of the woman that washes clothes'; and that may be the significance of the woman who is figured beside the infants in each of Cranach's paintings of Melancholy. Also, Saturn is sometimes depicted as a wooden-legged ancient of days with a watering-pot. Here, however, in true alchemical fashion, an ambivalent, or opposed, quality creeps in; for at times the idea of aridity or dryness is linked with the complex Saturnine mysticism. This is but one of its many ambivalencies.

Lead, the heavy, base metal, joined in alchemy with Saturn, the slow, gloomy planet, is often represented by a darkened symbol (Fig. 13); it is also sometimes brought into the black stage of the Great Work. The central figure in Dürer's design likewise 'leans forward massively' with darkened face, because, in Milton's words, her

> saintly visage is too bright
> To hit the sense of human sight,
> And therefore to our weaker view
> O'erlaid with black, staid Wisdom's hue.

Number, Harmony, and Music

Measurement is dependent upon number, which therefore enters, with measurement, into the Saturnine mysticism. As a token of this, Dürer's 'Melencolia' contains a magic square of the fourth order, showing ingeniously the date of the engraving (1514) in the two central squares of the bottom row.

Quite apart from this link with the Saturnine symbolism, number holds an independent position of great importance in alchemy. Indeed, from very early times certain numbers were endowed with mystical and magical properties; and even at the present day there are those who view the number 13 with superstitious misgivings. As far back as 1550 B.C., the Papyrus Ebers prescribed the powdered tooth of a hog, placed inside four sugar-cakes, as a remedy for indigestion. In ancient Greece, the Pythagoreans exalted the importance of number to such a degree that in it they sought for the origin and interpretation of the Cosmos. Of equal significance was the later view of Plato that Nature is framed upon a mathematical basis, and that it is in mathematics that the ultimate realities are to be found.

Number came into alchemical prominence partly from the Greek schools of thought and partly also from the doctrines of cabbalism. There was a cabbalistic system of expressing words in numerical terms, according to which, for example, the name of gold had the value (1x2x3x4)8, or 192. Had they possessed a knowledge of atomic weights, alchemical mystics would no doubt have pointed out that this number falls within a few units of the atomic weight of gold! Cabbalism also maintained the ancient importance of the number four, in such mystical quaternions as the corners of the earth, the elements, the winds, spirits, guardian angels, and rivers of Paradise. To these, the modern mystic might well add the quadrivalent carbon atom of Kekulé (p. 175) and the tetrahedron of van't Hoff (p. 188). Like most of their conceptions, the numerical notions of the alchemists are usually dismissed nowadays as the baseless fabric of a vision. Nevertheless, Hoefer, an eminent French historian of chemistry, wrote in 1866: 'mystical combinations based upon numbers, are, it will be said, nothing more than reveries of an ancient day. Well and good. But in our own time, when so much authority is attached to experiment, has a better explanation been devised for atomic combinations, based upon arithmetic and geometry?'

Seven was a favourite number, because it applied to the known metals, the major heavenly bodies, the days of the week and so forth. Sometimes even the colours of the Great Work were represented by numbers, although these did not coincide with the wave-lengths of modern science! Moreover, the number ten, derived from the tetractinal summation of Pythagoras $(1+2+3+4)$, was allocated to the Philosopher's Stone. The importance they attached to the sequence of the low integral numbers was emphasised repeatedly by alchemical writers in their allusions to the Stone. For example, Basil Valentine stated that 'all things are constituted of three essences—namely, mercury, sulphur, and salt. . . . But know that the Stone is composed out of one, two, three, four, and five. Out of five—that is the quintessence of its own substance [Aristotle's *quinta essencia*]. Out of four, by which we must understand the four elements. Out of three, and these are the three principles of all things. Out of two, for the mercurial substance is twofold. Out of one, and this is the first essence of everything which emanated from the primal fiat of creation.'

The numerical conception of the Stone is brought out clearly in a table of names and symbols published (in German) at Nuremberg in 1766, and reproduced below:

four Elements	*three Principles*	*two Seeds*	*one Fruit*
Fire 🜂			
Air 🜁	Sulphur 🜍	Masculine ☉	
Water 🜄	Salt ⦶		Tincture ♁
Earth 🜃	Mercury ☿	Feminine ☾	
from God	*from Nature*	*from Metals*	*from Art*

Fig. 20. A Numerical Conception of the Stone

Returning now to ancient Greece, we find that the Pythagoreans recognised the existence of definite numerical relationships between the notes of musical scales; and so number became associated in their minds with harmony. Moreover, they considered that the positions and movements of the celestial bodies were subject to numerical laws, and, further, that their harmonic motions gave rise to a celestial music. Since the Pythagoreans supposed that the stars and planets moved in crystalline spheres, having the earth as their common centre, this imagined music became known as 'the music (or harmony) of the spheres.' It found many echoes in the writings of later ages. Thus, Shakespeare alludes to 'certain stars' that 'shot madly from their spheres, to hear the sea-maid's music'; and in another beautiful passage he exclaims,

> Look how the floor of heaven
> Is thick inlaid with patines of bright gold:
> There's not the smallest orb which thou behold'st
> But in his motion like an angel sings.

From such considerations it is not surprising that music entered into alchemical conceptions and practice; for besides flourishing among the Greeks and Arabs, music provided an accompaniment from very early times to the rituals and ceremonies of religion, magic and necromancy. Alchemical designs often contain representations of musical instruments, sometimes borne by mythological performers; and both Hermes and Minerva were recognised as patrons of the musical art. To a certain extent, therefore, music was considered to exert a beneficial effect upon alchemical operations. For example, Norton, an alchemist with a strong practical cast of mind, wrote in 1477: 'Joyne them together also *Arithmetically*, By suttil Numbers proportionally . . . Joyne your Elements *Musically*.'

It seems likely that the mystical alchemists in particular, in the course of their prolonged efforts to bring every conceivable favouring influence to bear upon the operations of the Great Work, may sometimes have carried out these operations to the accompaniment of musical chants or incantations, such as would be familiar to them in their religious devotions. There is a very suggestive illustration[1]

[1] *Prelude to Chemistry*, Plate 52.

in a work published originally by Heinrich Khunrath in 1595 and reissued posthumously at Hanau in 1609, a few years before the appearance of Maier's *Atalanta Fugiens*. Khunrath was a Hermetic mystic of the deepest dye. Here he is shown in person, with his characteristic pointed beard, praying at the oratory; while behind him in the same room may be seen the typical apparatus and materials of an alchemical laboratory. Perhaps he is praying in the words used by George Ripley, a century earlier: 'O Unity in the substance, and Trinity in the Godhead. . . . As thou didst make all things out of *one* chaos, so let me be skilled to evolve our microcosm out of *one* substance in its three aspects of Magnesia, Sulphur, and Mercury.'

As he prays, Khunrath fixes his gaze upon a pentagram, the badge of the Pythagoreans. Upon an adjacent table lie several musical instruments, among them a viol, a harp, and two lutes; below them an inscription in Latin states that 'sacred music disperses sadness and malignant spirits.' It seems likely that music was regarded as an antidote to alchemical melancholy, as well as exerting a beneficent influence upon alchemical processes.

The last and most complete record of an attempt to establish an alliance between alchemy and music is to be found in Count Michael Maier's *Atalanta Fugiens*. Here, each of the fifty Latin epigrams (p. 66) attached to the engravings and embodying with them an alchemical conception, is set to music of a curious and distinctive kind. Maier's so-called 'fugues' are in reality a very rigid and mechanical type of canon arranged for three voices. The two voices in canon are called 'Atalanta Fugiens,' or the fleeing voice, and 'Hippomenes Sequens,' or the pursuing voice (which always lags behind the first voice in the canon). The third voice, 'Pomum Morans,' is the delaying voice (the apple in the path). These three voices, in their alchemical interpretation, signify the elusive Stone, the pursuing adept, and the obstacles in his way.

Musically, the compositions take the form of a canon in two parts against a *canto fermo*. The fifty varied canons have to be brought into harmony with a sensibly invariant *canto fermo*, and so the composer is faced with a formidable task, almost as impossible of satisfactory completion as the achievement of the Stone. In such compositions the *canto fermo* was usually a well-known musical theme, and Maier used for his purpose a familiar church melody dating as far back as the eleventh or twelfth century.

Presumably Maier intended these alchemical 'incantations' to be sung by an alchemic choir at critical moments during the coction of the Philosopher's Stone, under the simultaneous influences of prayer and the heavenly bodies. Whether the 'fugues' were ever applied by Maier or other alchemists at Prague or elsewhere in practical operations of this kind is not known; certainly, more than three centuries later a selection of this alchemical music was sung, in 1935, at the Royal Institution, London, by the choir of the ancient University of St. Andrews, a seat of learning founded in the days of Nicholas Flamel. The singers wore their traditional gowns of scarlet, symbolic of the colour of the Philosopher's Stone—but nothing changed to gold!

This chapter has traced only a few of the more obvious strands of the intricate web of alchemy, which an eminent French writer, Poisson, has epitomised in the following words: 'Scholasticism with its infinitely subtle argumentation, Theology with its ambiguous phraseology, Astrology, so vast and so complicated, are only child's play in comparison with Alchemy.'

VI · THE DIVERSITY OF ALCHEMISTS

IF Mr. Pickwick had been as conversant with alchemy as with politics he might well have informed Count Smorltork that 'the word alchemist, sir, comprises of itself, a difficult study of no inconsiderable magnitude.' Throughout the long millenium of alchemy there were legions of alchemists, and these were of many kinds, ranging from rough, unlettered 'labourers in the fire' to cultured and erudite philosophers, visionaries, and religious mystics. In other words, the genus alchemist was comprised of many species and varieties.

Pseudo-Alchemists

A classification of alchemists, starting at the lowest level, must begin with a species which does not really belong at all to the genus. This species may be variously termed charlatans, quacks, impostors, or, using the most respectable term of all, pseudo-alchemists. These were the practitioners of roguery, who assumed the title of 'alchemist' solely to increase their professional status in the eyes of their patrons. Unfortunately for the reputation of alchemists in general, it is the pseudo-alchemist who has generally been called upon by lay writers to represent alchemy in general literature. In the pages of Scott, Dumas, and other romantic novelists, he may be an astrologer, magician, necromancer, or cheiromancer, like Galeotti Marti in *Quentin Durward,* or Guiseppe Balsamo, alias Cagliostro, in *Mémoires d'un Médecin.* Of all fictional 'alchemists,' the best known is probably Subtle, in Ben Jonson's play, *The Alchemist,* first staged in 1610, in London.

Subtle descends to still lower levels, for in 'rare Ben's' own words he is no better than a 'cheater' or 'coz'ner at large,' who envelops his discreditable operations in a bewildering web of alchemical verbiage. There is no doubt that Jonson modelled the figure of Subtle upon an actual prototype of that early Jacobean age in London. Of the three likely originals, John Dee, Edward Kelly, and Simon Forman, the last-named is actually mentioned by name in Jonson's earlier play, *Epicoene*, as a purveyor of love-philtres. All the evidence points to Forman as the 'alchemist' whom Jonson had in mind when writing this most famous and sparkling of all his plays.

Simon Forman (1552-1611) was born at Quidhampton, in Wiltshire. First apprenticed to a hosier, and then to a dealer in many things, including 'all poticary drugs and grocery,' he turned to teaching at the age of eighteen. Somewhat later he began to dabble in necromancy, and then to practise 'magik and phisick,' as he records in his diary. After repeated imprisonments for quackery, he obtained some kind of diploma from Cambridge and succeeded eventually in establishing a lucrative practice among the society ladies of London, whom he supplied lavishly with love-philtres, charms, enchantments, 'pictures in wax, crosses, and many strange and uncouth things,' including an enchanted nutmeg for the Countess of Essex, who had transferred her affections from her husband to Viscount Rochester and wished for reciprocation.

In 1593 Forman writes: 'This yere I stilled my strong water [*aqua vitae*], for the which I gote moch mony'; and he makes other references to this source of income. He reveals himself in his diary as cantankerous, credulous, and superstitious; and although he claimed to control 'the very sprites,' he was quite unable to manage his own womenfolk. His only claim to the title of alchemist—and here he transcends Ben Jonson's Subtle—lies in his few feebly sporadic efforts to prepare the Philosopher's Stone. On 26 September 1595 he records: 'This dai at 55 past 3 I bought a peyer of newe black stockins, cost 12s., and that morning I drempt of 3 black rats, and of my philosophical pouder which I was distilling of.' The 3 black rats were forerunners of evil, for later in the year, 'The 12. dai of Decemb. was a wonderfull unlucky dai for me. I brast 2 glasses and lest the water, and many things framed evill in my handes.'

Forman's final reference to the Stone followed soon after, in 1596, when the 3 black rats were still active; for, 'The 29. March A. Al. [one of his womenfolk] hit me in the mouth with her hand. The 5. of Aprill, Monday, A. Al. scratched me by the face that I bled . . . The 27. of Aprill in subliming, my pot and glasse brok, and all my labour was lost pro lapide [for the Stone].'

The popular impression of an alchemist as a 'cheater' or 'coz'ner at large,' owes a good deal also to Chaucer's *Canon's Yeoman's Tale*, which preceded *The Alchemist* by more than two centuries. In this relation, one of the most charming and realistic of the *Canterbury Tales*, the Canon is an 'alchemist,' and the Yeoman is his assistant. The Yeoman tells of his woeful experiences with two 'alchemists,' the second of whom belongs to the same species as Subtle, for he is nothing more than a swindling impostor. By means of rigged experiments, in which he shows himself to be a master of legerdemain, he convinces a credulous priest that he possesses the secret of transmutation into silver.

In one of his demonstrations he solicits his prospective victim's help in adjusting, in a hot charcoal fire, his 'crosselett' [crucible], already charged with an ounce of quicksilver and some of his powder of projection. 'Ye be right hot, I see wel how ye swete,' remarks the 'alchemister,' as he distracts the priest's attention by handing him a cloth to 'wype away the wete.' And then,

> This false canoun (the foule feend him fetche!)
> Out of his bosom took a fals*e* cole,
> In which ful subtilly was made an hole,
> And therein was put of silver metál
> An ounce, and stoppèd was withoute fayle
> This hole with wax, to kepe the metal in.

Fig. 21. An Alchemist and his Laborant at Work (*c.* 1520)

By the time the priest had 'wyped away the wete,' the prepared piece of charcoal had found its way into the crucible, and the 'alchemister' was working away assiduously with his bellows, intent upon this crowning operation of the Great Work. The heat volatilised the quicksilver, and the equal weight of molten silver sank down to the bottom of the crucible, which was eventually broken in order to expose the solidified noble metal. 'now, good*e* sirs, what wil ye better than wel?' exclaimed the sarcastically indignant yeoman at this point in his narrative.

So the avaricious priest was led to ask anxiously: 'What shal this réceyt cost*e*? telle me now.' 'Ye shal paye fourty pound, so God me save,' answered the 'alchemister,' with a show of reluctance; since, as he pointed out, 'save I and a freere, In Eng*e*lond ther can no man it make.' So the secret was handed over for the 'somme of fourty pound of nobles,' to the priest; and as for the 'alchemister,' in the trenchant words of the Yeoman:

> He went his way, and never the prest him sey
> After this day; and when this prest sholde
> Maken assay, at such tyme as he wolde,
> Of this receyt, far wel, it wold not be.

'*Labourers in the Fire*'

One of the earliest pictorial representations of an alchemical interior is to be found in a woodcut showing an alchemist and his assistant at work in a medieval laboratory (Fig. 21). This was executed about the year 1520 by Hans Weiditz, a celebrated illustrator of the Augsburg school of engravers and a contemporary of Dürer and Cranach. It affords a strong and lively representation of the subject, with an element of caricature which adds to the reality of the treatment. The alchemist is working at a hearth having a large pair of bellows installed in a permanent position at one side. The equipment includes also an

Fig. 23. Sendivogius makes Gold

(*See p. 88*)

Fig. 25. Paracelsus, 1493–1541 (*See p. 100*)

Fig. 27. La leçon de chimie au Jardin royal (*See p. 105*)

anvil, hammers, tongs, pincers, and other tools. Altogether the scene is reminiscent of an old-fashioned village smithy, rather than of a laboratory.

Weiditz's illustration is, however, a genuine presentment of a medieval alchemist of the exoteric, or uninformed, type. He is engaged in a typical operation, the nature of which explains at a glance why alchemical practitioners of this kind were often called 'labourers in the fire.' Because of their addiction to the bellows, they were also called 'puffers' or 'souffleurs.' 'I blowe the fyr til that myn herte feynte,' exclaimed the Canon's Yeoman in a *cri de cœur*. Much later, in the middle of the seventeenth century, Teniers poked fun at the uninstructed 'puffer' by representing him as an ape seated at an alchemical hearth and working away with a pair of hand-bellows, in ape-like imitation of the operations of his superiors in the alchemical hierarchy.

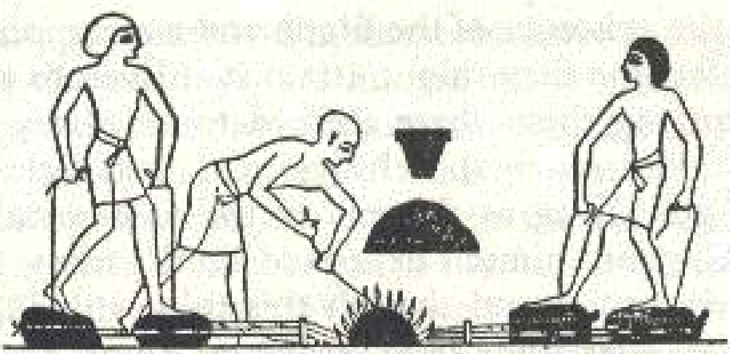


Fig. 22. Early 'Puffers' (Egypt, *c.* 1450 B.C.)

The art of 'puffing,' in order to promote combustion and attain a high temperature, stretches back into a remote antiquity. It has already been mentioned (p. 7) that the operations of Egyptian craftsmen who were engaged in the fusion of gold provided a theme for Egyptian artists so long ago as 2500 B.C. (Fig. 2). Another Egyptian drawing (Fig. 22), of about 1450 B.C., shows some remote ancestors of the medieval 'puffers' working two pairs of foot-bellows in the heating of a furnace, above which there is an inset suggestive of a crucible.

Time stood still for century after century in alchemy. Weiditz's illustration of 1520 therefore fits perfectly Chaucer's vivid account of the appearance and doings of the first alchemist of the *Canon's Yeoman's Tale*, which was written more than a century earlier. This first 'Canoun' of the *Tale*, who is encountered riding to 'Caunterbury toun' with the pilgrims, was a typical 'puffer'; and Chaucer's poem gives the most intimate account which has come down through the ages of the human relationships obtaining in such a laboratory. It is a fascinating study by one who had a first-hand knowledge of contemporary alchemical laboratories and of those who worked in them; for Chaucer took a great interest in the science of his day, and was indeed the author of a treatise on the astrolabe, which he wrote about the year 1391.

The species 'puffer' in alchemy embraced men of varied character and disposition; but they shared a common belief in the existence of the Stone and a common hope that by good fortune they might attain it. Even to the crudest worker among them there seemed to be always a chance that he might reach the elusive goal, and light upon the purse of gold lying at the end of the alchemical rainbow. As the 'Canoun' himself expressed it, 'Us most*e* putte oure good in áventúre, and though this thing myshappèd hath as now, another tyme it may be wel y-now.' Or, in the words that Ben Jonson ascribed to Subtle two centuries later, he who persevered and came in time 'to be a great distiller' would be able to 'give a 'say (I will not say directly, but very fair) at the Philosopher's Stone.' So the ever-hopeful 'puffer' was led on to squander all his worldly goods in the vain pursuit. A glance at the attire of Weiditz's 'puffer' bears out Chaucer's description: 'His over cote it is not worthe a myte . . . it is al filthy and to-tore.' The other pilgrims look wonderingly at the attire of one who is reputed to be able to pave 'Caunterbury toun . . . al of silver and of gold,' and they ask the Yeoman, 'Why is thy lord so slottish . . . and yet hath power better clothes to buy?'

It was not only the clothes of these sorely-tried 'labourers in the fire' that suffered during the wearisome hours spent at their hearths and furnaces and in the fumes of their laboratories. The Canon's Yeoman laments that,

> I am so usèd in the fyre to blowe,
> That it hath chaungèd al my colour I trowe . . .
> Though I was wont to be right fresh and gay
> Of clothing, and of other good array,
> Now may I were an hose upon myn heed;
> And where my colour was both fressh and red,
> Now it is wan, and of a leden hewe.

Like Tonsile in Norton's *Ordinall*, a century later, 'With weeping Teares he said his heart was fainte, for he had spended all his lusty dayes in fals Receipts, and in such lewde assayes.'

Materials, processes and laboratories have changed much since those distant days, yet human nature in general and the feelings and emotions of laboratory workers in particular still remain much the same. At the present day, just as in the laboratory depicted so vividly in the narrative of the Canon's Yeoman, it is possible to say, although in a somewhat modified language: 'Whan we be ther where we shul exercise oure elvish craft, we sem*e* wondrous wyse, Oure term*es* be so lerned and so queynte.' Even in the fourteenth century the jargon of science fell strangely upon the ears of laymen.

Again, the accidents and annoyances of modern laboratory work, although different in detail from those that vexed the 'puffers,' still evoke similar human responses. The experience of an unlucky breakage, causing the loss of weeks of labour, creates a spiritual bond between a modern research worker and his ancestors of six hundred years ago, when he reads:

And wit ye how? ful ofte it happeth so,
The pot to-breketh, and farwel, al is go . . .
There never was suche wo or anger or ire
As when oure pot is broke, as I have sayd,
Everyman chideth, and thinketh him ill paid.
Some sayd it was too long on the fyr-making;
Some sayde nay, it was on the blowyng;
(Than was I feard, for that was myn office).

The first alchemist described in the *Canon's Yeoman's Tale* was only a poor uninformed 'puffer'; yet, in such distressing circumstances, he did what he could to hearten the workers and to assure them that no blame attached to anybody for a mishap due to the inscrutable workings of fate, allied with the inherent malignity of matter. 'I am right certyn,' asserted the Canon, 'that the pot was crasèd'; and he adjured his discomposed staff to recover anything possible from the wreckage: 'As usage is, let swoope the floor up soon; pluk up your hertes and be glad and boon.' So the bits and pieces are 'i-swoped on an heep,' gathered on a strip of canvas, and sifted through a sieve, whereby was 'y-plukkèd many a throwe.'

Throughout Chaucer's description of the 'puffer' type of alchemist there is a strong and repeated emphasis on the note of poverty. 'Al that I hadde, I have y-lost therby, and God wot, so hath many mo than I,' bemoans the Yeoman, after seven years of service to the Canon. 'That slippery science hath made me so bare,' he continues, 'that I have no good, wher that ever I fare.' The besotted 'puffer' not only reduces himself to poverty, but also impoverishes his credulous friends and acquaintances by borrowing from them, often in good faith, in the hope of multiplying their gold by alchemical means and keeping a commission for himself. In the words of the Yeoman:

To moche folk we bring but illusioún,
And borrow gold, be it a pound or tuo,
Or ten or twelve, or many sommes mo,

And make them thinken at the leaste weye,
That of a single pound we can make tweye.
Yet is it fals.

Having learned his alchemical lesson by bitter experience, the ill-used Yeoman ends:

Than thus conclude I, since God on high
Wil not that philosóphres signify,
How that a man shal come unto this stoon,
I counsel for the beste, let it goon.

'*Sons of Hermes*'

The informed adepts, or esoteric alchemists, who pinned their faith to the Emerald Table and regarded themselves as the 'sons of Hermes,' bulk very largely in the long history of alchemy, especially as so many of their voluminous writings are extant, either in manuscript or in print. The 'puffers,' on the other hand, left comparatively few literary remains. The primary aim of the 'puffer,' although he might often share the religious convictions of the adept, was to obtain the Stone as a key to material wealth and well-being. Many of the adepts, however, looked to the Stone primarily as a philosophical and religious goal, although doubtless they had a secondary interest in it as a source of wealth, health, and long life. Flamel, for example, after describing his successful transmutation (p. 53), remarks almost nonchalantly, 'I had indeed enough when I had once done it,' and goes on to give the impression that his chief interest was in the nature of the achievement and the contemplation of 'the *Admirable* [wonderful] *workes of Nature*, within the *Vessels*.'

A great deal of information about the character and views of the adepts, and also about the nature of their operations, is to be found in Elias Ashmole's *Theatrum Chemicum Britannicum* (1652). This invaluable selection of twenty-nine English alchemical writings illustrates the tendency of the adepts to express their ideas in verse, possibly because they considered this medium as particularly favourable to 'the noble Companie of true Students in holy Alchimie, whose noble practise doth hem teach to vaile their secrets with mistie speech,' as the author of *The Hunting of the Green Lyon* remarks in one of Ashmole's poetical items. The three chief items in this collection are: 'The Ordinall of Alchimy. Written by Thomas Norton of Bristoll'; 'The *Compound* of Alchymie. A most excellent, learned, and worthy worke, written by Sir *George Ripley*, Chanon of *Bridlington* in *Yorkeshire*, Conteining twelve Gates'; and 'The Tale of the *Chanons Yeoman*. Written by our Ancient and famous English Poet, *Geoffry Chaucer*.'

The *Ordinall of Alchemy*, which Norton wrote in 1477, affords a particularly clear picture of an adept; for Norton combined a deep knowledge of alchemical doctrines with practical ability and directive capacity of a high order. He exercised his cryptic skill by concealing his authorship of the *Ordinall* in an acrostical cipher. As a thorough alchemist, he wrote his poem in seven chapters, with a preface, or 'Proheme.' Certain initial letters taken from the first seven of these sections, together with the last line of the seventh chapter, inform the skilled reader that,

> Tomais Norton of Briseto
> A parfet *Master* ye maie him call trowe.

The first printed version of the *Ordinall* was published in Latin, by Michael Maier, at Frankfurt in 1618: according to Ashmole, Maier visited England expressly for the purpose of acquiring a sufficient knowledge of English to enable him to undertake the translation.

It is thought that Norton received his alchemical instruction and initiation from Ripley, a recognised master of the Hermetic art who had studied in Italy. Norton does not indeed identify his master; but he states that he was called to visit him, whereupon,

This *Letter* receiving, I hasted full sore,
To ride to my *Master* an hundred miles and more;
And there Forty days continually,
I learned all the secreats of *Alkimy*.

Norton was fortunate to be chosen as a suitable neophyte; for on his own showing in the *Ordinall* the doctrines of 'holi Alkimy' could be imparted only by word of mouth from a divinely appointed Master, who could scarcely have taken large classes of pupils seeing that 'of a *Million*, hardly *three* were ere Ordained for Alchimy.' In order to preserve the doctrines of esoteric alchemy under a Hermetic seal, the neophyte had to take a 'most sacred dreadfull Oathe' to abstain from all aspirations to great dignity and fame, 'And also that he shall not be so wilde To teach this secreat to his own childe.' Membership of the esoteric fraternity was not hereditary. The acquirement of this portentous knowledge had to be blended with humility, seeing that,

Almighty God
From great Doctours hath this *Science* forbod,
And granted it to few Men of his mercy,
Such as be faithfull trew and lowly.

From all this it is clear that, in the opinion of the adepts, the great secret, once discovered, had to be kept as a holy mystery, lest its publication and exercise should bring disaster to humankind.

Norton's putative master, Ripley, in his *Compound of Alchymie*, a prolix composition also written in verse, dilates upon the usual alchemical themes, such as the processes and duration of the Great Work, colours, tingeing, multiplication of 'the Medicine,' astral influences, and prayer. Norton covers much the same ground, writing always with great circumspection, lest he should give away too much information. For instance, in mentioning 'sal armoniak' and the 'sulphur of metals,' as materials used in the Great Work, and talking of 'there lies the snowy wife wedded to her red spouse,' he feels that he may have been indiscreet, for he adds:

> This secrete was never before this daye
> So trewly discovered, take it for your praye;
> I pray *God* that this turne not me to Charge,
> For I dread sore my penn doeth too large:
> For though much people perceive not this Sentence,
> Yet subtill *Clerks* have too much Evidence;
> For many *Clerks* be so cleere of witt,
> If thei had this ground, thei were sure of it.

Norton was not obsessed, like so many of the adepts, with the mystical aspects of alchemy. He was level-headed and endowed with an outstanding practical aptitude. Unlike most alchemists of his period, he attached importance to weighing his materials, as he says, 'with subtill balance and not with Eye.' A contemporary manuscript copy of his *Ordinall*, beautifully written and ornamented, contains an illustration[1] showing an adept, probably Norton himself, seated in his laboratory before a balance: this is said to be the earliest known representation of a balance enclosed in a case. Norton was especially skilled in designing and operating alchemical furnaces (p. 37); moreover, he displays in the *Ordinall* a discriminating knowledge of laboratory ware of various shapes, materials, and uses. 'Manie Claies woll leape in Fier,' he writes in one place; 'Such for Vessells doe not desire.'

Unusually again, Norton refers to the problems of laboratory upkeep and administration in the fifteenth century. If workmen were hired by the day, they could be dismissed summarily if need be; but married ones disliked this kind of contract. It was difficult to get skilled and trustworthy help, and inadvisable to have a mixed staff of men and women. His servants were given to 'deceipt,' 'sleeping by the fire,' dishonesty, and negligence. Moreover, although he insisted that his 'ministers' must be

[1] *Prelude to Chemistry*, Plate 34.

'clenly of hands, in Tuching curious [careful],' yet they were apt to be 'filthie of hands and of sleeves.' Since Norton's operations were continuous, he ran his 'ministers' in shifts, so 'That one halfe of them must werke While the other Sleepeth or goeth to Kerke.'

Besides all this, to his 'greate paine and much more woe,' he suffered from the theft of his Elixir of Life by a merchant's wife, a calamity which led to the reflection,

> Soe in this worke there is no more to saine,
> But that every *Joy* is medled [mingled] with his *paine.*

Norton may be pictured as a representative of the first note in a gamut of alchemical adepts, leading onwards through such nebulously minded mystics as Michael Maier, who had no aptitude for practical operations, and ending up with 'hierophants of the psychic side of the *magnum opus*,' like Khunrath, who carried out his religious exercises in an oratory-laboratory (p. 72) in which the very apparatus bore an attenuated and spiritual appearance. Adepts of this type exerted no influence upon the progress of alchemy towards chemistry.

A somewhat exceptional position in the gamut of alchemical adepts must be assigned to the Polish nobleman and alchemist, Michael Sendivogius, whose romantic story is inextricably bound up with that of Alexander Seton, a reputed Scottish alchemist who has been termed 'the chief martyr of alchemy.'[1]

Sendivogius acquired an unsurpassed reputation as a goldmaker. At the same time his alleged authorship of the *Novum Lumen Chymicum* (1604), a work which attracted the serious attention of Sir Isaac Newton, gives him high rank among alchemical adepts. Alexander Seton remains an alchemical shadow; but Sendivogius was an actual person. His Polish name is rendered more accurately as

[1] The fascinating story of Seton and Sendivogius is related in detail in *Humour and Humanism in Chemistry*.

Michael Sedziwój. Born in 1556 or 1566 at Sacz, he is said to have lived until eighty years of age. Sendivogius is a Latinised form of a Polish name, with the literal meaning, 'he who judges warriors.' This 'noble Pole' made use of a modified spelling of his name, 'Micheel Sandivogius,' in the form of an anagram, 'divi Leschi genus amo,' signifying 'I love the race of the divine Poles,' since Lech (or Leszek) was the legendary founder of the kingdom of Poland.

An edition of *Novum Lumen Chymicum* published at Nuremberg in 1766 contains what is described as 'a true portrait of Sendivogius.'[1] A much later painting by the famous Polish artist, Jan Matejko (1838-93) is reproduced in Fig. **23**. The original painting was formerly in a collection at Warsaw, but it may have been removed or destroyed towards the end of the Second World War. The artist depicts Sendivogius in the act of transmuting a silver coin into gold. King Sigismund III, to whom Sendivogius had been introduced by Marshal Wolski, and the Reverend Father Piotr Skarga, S.J., watch the process with absorbed interest. The other figures also represent real persons. The scene is in the royal castle at Cracow, and the fireplace here depicted was still extant in 1950.

The Practical Tradition

An exponent of the purely spiritual aspect of alchemy (de Givry), in a work published so late as 1931 stated: 'The operation of the Philosopher's Stone does not belong to the realm of pure chemistry. The method described with so remarkable a unity of doctrine excludes any idea of research or tentative procedure, and is incompatible with the abundant experimentation involved in modern chemistry both organic and inorganic. . . . It is not then from alchemy, as often stated, that modern chemistry derives, but actually from the erratic work of the Puffers.'

[1] *Humour and Humanism in Chemistry*, Fig. **16**.

This statement needs considerable qualification. In the first place, these unchanging doctrines and conceptions denoted a condition of intellectual stagnation. Secondly, although chemistry owes something to the 'puffers,' it is also indebted to adepts of the calibre of Norton and Basil Valentine. The debt of chemistry extends still further, far back through the long age of alchemy and beyond, to the skilled craftsmen, the artisans, the experienced workers in metals, minerals, dyeing and other arts, and to still others who dealt in a practical way with the multifarious products of inorganic and organic nature. These were the 'technologists' of the ancient civilisations, and it is indeed in them that the first faint stirrings of the knowledge that led on to alchemy and eventually to chemistry may be discerned (p. 7).

Later, much practical experience was gained in the experiments of Alexandrian artisans, reflected in the celebrated Formula of the Crab (Fig. 3), to produce imitation gold; and afterwards in the efforts of the alchemists of Islam to produce real gold artificially. Among these alchemists, Jabir ibn Hayyan (Geber, p. 17) obtained a considerable command of practical operations, and he experimented not only with mineral materials, like the Alexandrians, but also with a wide variety of animal and vegetable products. He knew how to prepare cinnabar from quicksilver and sulphur, and was familiar with sal ammoniac. Jabir died early in the ninth century, and soon after him came Al-Razi (Rhases), the greatest of all medieval physicians and also an outstanding worker in alchemy. He was familiar with a surprising range of laboratory apparatus and equipment, and also with a large number of minerals and inorganic substances.

The practical tradition of Islam percolated slowly into Western Europe in the steps of the translators (p. 14); but, in the words of Lacroix, 'more profit would have been derived from consulting the daily note-book of an artisan of that period than the farrago of those who were engaged in the Great Work.' The translators of the twelfth and thirteenth centuries, such as Robert of Chester and Michael Scot, made their indirect contributions to the practical tradition, although they were not practical workers; and the latter writer's summary of the alchemy of the day, as he saw it, is of considerable interest. In his *Liber particularis*, written about 1230 in Sicily, at the court of the Emperor Frederick II, this most eminent Briton to secure a place in the history of medieval Italy referred the composition of metals to the sulphur-mercury theory of the school of Jabir; he regarded gold as a potent medicine; and he recognised the practicability of tingeing metals or alloys to simulate gold or silver. However, he did not mention transmutation or the Philosopher's Stone. This omission is notable as indicating that the gold-making mania of the fifteenth century and later had not yet set in, and that Michael Scot's point of view was that of the Graeco-Egyptian makers of imitation gold and silver, rather than that of the later 'puffers' and adepts of Western Europe.

The translators were succeeded by the so-called encyclopaedists, of whom Albertus Magnus and Roger Bacon, both of whom lived throughout the greater part of the thirteenth century, were the most famous. Their extensive writings were invaluable in summarising and expounding the new knowledge, including that of alchemy. Neither the *Doctor Universalis* (Albertus) nor the *Doctor Mirabilis* (Bacon) could be called an alchemist, although both of them had an experimental familiarity with alchemy, in addition to a profound knowledge of its literature and traditions. Bacon in particular recognised the importance of mathematics and experiment in science; and in practical work he advanced beyond the contemporary work and experiments of artisans and alchemists. It is incorrect to assert that he discovered gunpowder; but it is a manifestation of his genius that he realised its inherent power. He improved its quality and strength, and was certainly one of the first to bring about an artificial chemical explosion. This achievement with gunpowder was rendered possible by purifying the crude 'villainous saltpetre' through crystallisation from hot water.

Bacon was imbued with the secretive instinct of the alchemists; for in his tract of 1242 he concealed the vital information for making a potent gunpowder (from saltpetre, charcoal and sulphur) in an anagram, shown in italics in the following operative sentence: 'Sed tamen salis petrae *luru vopo vir can utri* et sulphuris; et sic facies tonitrum et coruscationen, si scias artificium.' If this cryptic expression is transcribed as R. VII PART. V NOV. CORUL. V and expanded into 'recipe vii partes, v novellae coruli v,' the whole sentence then reads: 'But of saltpetre take 7 parts, 5 of young hazel-twigs, and 5 of sulphur; and so thou wilt call up thunder and destruction, if thou know the art.' It would perhaps be exalting the prescience of the *Doctor Mirabilis* [the Wonderful Doctor] to discern also in this anagram an allusion to Guy Fawkes' Day, falling on 5th

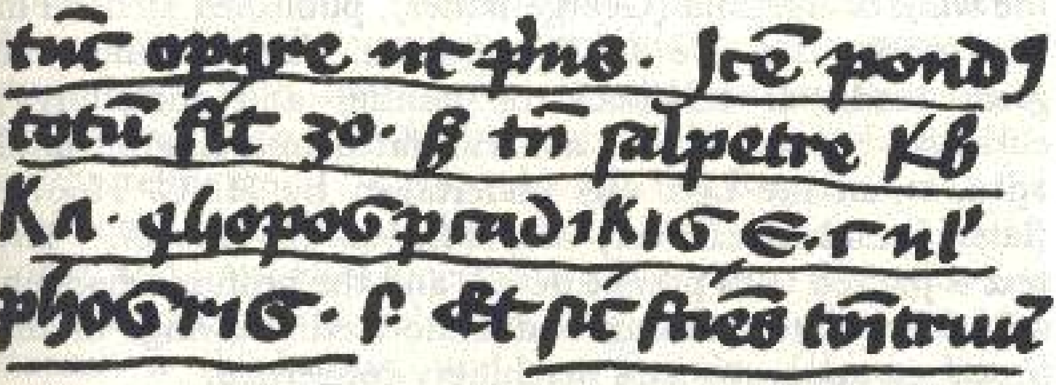


Fig. 24. Roger Bacon's Gunpowder Anagram (13th century)

November! A more complex form of the anagram may be seen in a manuscript version of Bacon's tract contained in the British Museum (Fig. 24).

The purifying and testing of the constituents of gunpowder and other practical operations of the incipient science of chemistry are described and illustrated in the *Codex Germanicus*, of the mid-fourteenth century. For example, a drawing[1] with a strikingly modernistic look, illustrates a strange and unlikely test for the purity of sulphur, which is nevertheless genuine. An accompanying explanation, written in medieval German, states: 'If thou wilt try whether sulphur be good or not, take a lump of sulphur in thine hand and lift it to thine ear. If the sulphur crackle, so that thou hearest it crackle, then it is good; but if the sulphur keep silent and crackle not, then it is not good.'

The introduction of printed books, with illustrative woodcuts, gave a great impetus to the spread of information about operative chemistry. Brunschwick's *Buch zu Distillieren* ('Book of Distillation') was one of the earliest of such works to appear; it was written in German, instead of the usual Latin, and its bold woodcuts also helped to make it more easily intelligible to those who were interested in the processes concerned. These numerous woodcuts were the first illustrations of the kind to depict chemical apparatus and operations.[2] Even more important was the work of Agricola (George Bauer), published at Basel in 1556 under the title *De Re Metallica*. This became the great medieval text-book of mining and metallurgy; curiously enough, it was not translated into English until 1912, when the task was undertaken by H. C. Hoover (later President Hoover) and Mrs. L. H. Hoover. The text is packed with precise detail, and the profuse woodcuts afford accurate working and annotated drawings of the processes, apparatus and machinery concerned.

Soon after Agricola's classic, came Libavius' *Alchemia*, of 1597. The massive 1606 edition, entitled *Alchymia*, with commentaries, weighs about ten pounds. The work is a blend of alchemical mysticism and symbolism (p. 41) with sound chemical knowledge. Besides the emblematic designs (Fig. 14), it contains clear drawings of apparatus, and even of a 'chemical house,' or laboratory, shown both in plan

[1] *Prelude to Chemistry*, Plate 8.
[2] *Humour and Humanism in Chemistry*, Fig. 9.

and elevation. This formidable work has sometimes been termed the first text-book of chemistry, since it contains clear descriptions of so many chemical substances and processes, including 'spiritus fumans Libavii' (stannic chloride), sugar of lead, sulphate of ammonia, the burning of sulphur with saltpetre to give oil of vitriol, the preparation of sugar candy, and the extraction of alcohol from fermented liquors.

A more spectacular series of mystical outpourings and emblems of a high alchemical standard, blended with sound chemical knowledge and practical ability, is evident in the works written and published under the pseudonym of Basil Valentine (p. 54). Indeed, Basilius' *Triumphal Chariot* of *Antimony*, first published at Leipzig in 1604, has even been described as the first monograph on a chemical element. The strange medley of mysticism and chemistry written by this Jekyll and Hyde, or schizophrene, of alchemy is shown by comparing his remarks on the Ninth Key (p. 57) with the following passage from his celebrated work on antimony. 'Take two parts of Hungarian Antimony [stibnite, antimony sulphide], and one part of steel; melt with four parts of burnt tartar [potassium carbonate] in an iron basin, such as those in which goldsmiths refine gold. Cool, take out the Regulus [metallic antimony], remove all impurities and scoriae, pulverise finely, add to it, after ascertaining its weight, three times as much burnt tartar; melt, and pour into a basin as before. Repeat a third time, and the Regulus ['Little king'] becomes highly refined and brilliant. If you have performed the fusion properly—which is the point of greatest importance—you will have a beautiful star of a brilliant white. The Star is as distinct as if a draughtsman had made it with a pair of compasses.' These instructions, giving even the weights of the reagents, are worthy of inclusion in a modern text-book of practical chemistry; but the meaning is not so obvious when Basilius continues, 'This Regulus, or Star, may be carried through the fire with a stone serpent [heated with a solid corrosive], till at length it consumes itself, and is completely joined to the Serpent.'

It was the combined work of craftsmen, artificers, practical alchemists, 'puffers,' and adepts that opened out and cleared the long and tortuous road leading from alchemy to modern chemistry. Of them all we may say, in some words of Kingsley: 'Most of them were poor; many all but unknown in their own time, many died and saw no fruit of their labours. . . . Of some the very names are forgotten. But though their names be dead, their works live, and grow and spread over ever fresh generations of youth, showing them fresh steps towards that temple of wisdom which is the knowledge of things as they are.'

VII · THE PARTING OF THE WAYS

THE opening of the sixteenth century was marked by a great forward surge of the Renaissance, that transitional movement in Europe between the medieval and modern order of Western civilisation. Many diverse influences were coming at that time into a common focus. Among them, the impact of the wonderful flood of rediscovered classical knowledge was gathering force; the power of the new art of printing was beginning to take effect; and the confines of the known world were rapidly expanding as a consequence of the voyages of Columbus (1492), Vasco da Gama (1497), and Magellan (1521). Fresh horizons of the material and intellectual world were opening with a rapidity hitherto unknown. Doctrines and conceptions that had held fast throughout the rigid period of medievalism now began to be questioned and assailed.

In this new and stimulating atmosphere there arose many pioneers of a fresh order. Early among them came Luther, whose success in the struggle to burst the bonds of religious orthodoxy and tyrannic authority found a dramatic expression in his public burning of the Papal Bull of Condemnation at Wittenberg, in 1520. Twenty-three years later, two equally significant upheavals in science found expression in two great works printed in 1543. Copernicus' *De Revolutionibus Orbium Coelestium* revolutionised the most ancient of sciences by asserting that the earth was a planet revolving around the sun, instead of being the hub of the universe, as depicted in the hoary Ptolemaic system; and Vesalius' *De Fabrica*, the foundation work of anatomy, brought about an advance of equal importance in biology.

Even alchemy, apparently so firmly entrenched, did not remain unaffected in the new, enquiring and critical atmosphere. And in step with alchemy, at this crucial epoch, marched medicine. The assailant of this apparently impregnable twin fortress was a remarkable man, even in that remarkable age; and he burst upon the scene bearing an impressive name worthy of his task.

Paracelsus

Shakespeare, in reply to his own question, 'What's in a name?', remarked that 'a rose by any other name would smell as sweet.' A similar judgment could hardly be applied to Philippus Theophrastus Aureolus Bombast von Hohenheim (or, more correctly, Banbast von Hohenhain), who, fortunately, was called Paracelsus for short. Without this impressive string of names, which he built up as he went along (for he was christened plain Philip), it seems doubtful whether Paracelsus would have been able to divert the twin streams of alchemy and medicine into new channels. This remarkable feat he accomplished by means of shock tactics, in which his formidable name must have carried considerable weight.

Paracelsus was born in 1493, near Einsiedeln, a few miles south of the Lake of Zürich. He was, in his own words, 'a Schwyzer by birth . . . brought up among the fir-cones, neither subtle nor superfine'; and in later life he showed the rough and undaunted fighting spirit of the men of this Swiss canton. In 1502 his father, William von Hohenheim, removed to Villach in Carinthia, where he became city physician and teacher in the mining school. Here the young Philip gained acquaintance with unlettered Tyrolean villagers, miners, and craftsmen, as well as with learned Carinthian monks. Later he studied spasmodically in many universities, and became a great wanderer over Europe and the adjacent fringes of Asia and Africa. 'Thus I began to learn,' he wrote in 1536, 'for many years in the universities of Germany, Italy, and France, seeking out the true foundation of medicine. I was not content with their teachings, nor with writings and books, and wandered further towards Granada, Lisbon, through Spain, England, Brandenburg, Prussia . . . and through other lands besides. . . . And in all these countries and places I was diligently investigating and enquiring into the certain and true art of medicine. This I tried not only with learned doctors, but also at the hands of barbers, bath-keepers or shearers, and with experienced surgeons; even with old women, with necromancers . . . with the alchemists and in monasteries; with the nobles and with the common people, with the cleverest and with simpletons.' He seems to have obtained his baccalaureate in Vienna about 1511, and he took his doctorate at Ferrara in 1515. Thereafter he assumed the cognomen of Paracelsus, applicable to one who had surpassed the learning of the celebrated Roman physician, Celsus (first century A.D.).

Armed with knowledge and ideas acquired from so many sources and with experience of all sorts and conditions of men in the rough-and-tumble world of his time, Paracelsus did not hesitate to attack, often in violent and scurrilous language, what he considered to be the malpractices and abuses of contemporary physicians and alchemists. Of the latter he said scathingly that 'they carried golden mountains in their heads before they had put their hand to the fire.' Like Roger Bacon long before him, and Francis Bacon in the following century, he pinned his faith to experiment, observation, and experience. Of the Parisian doctors he said scornfully, 'they know not what *experimentum* means, and how experiments are made. They despise all others and yet are nothing but utter ignoramuses themselves.' For the 'lazy so-called' physicians who prefer dogma to experiment it suffices if 'like apothecaries, they jumble a lot of things together and say *Fiat unguentum* . . . yet if medicine were handled by artists, a far more healthy system would be set on foot.' By 'artists' he meant the so-called spagyrists, or alchemistic physicians, of whom he spoke approvingly:

'They [the spagyrists] are not given to idleness, nor go in a proud habit, or plush and velvet garments, often showing their rings upon their fingers, or wearing silver daggers by their side, or fine and gay gloves upon their hands; but they diligently follow their labours, sweating whole days and nights by their fiery furnaces. . . . They put their fingers amongst the coals, the lute, and the dung, not into golden rings. They are sooty and black like smiths and colliers, and do not pride themselves upon a sleek countenance. They do not gossip with their patients and vaunt their own remedies. They know well that the work must glorify the workman, not the workman his work. They reject such vanities, and delight to labour in the fire and learn the steps of alchemy. These are distillation, solution, putrefaction, extraction, calcination, reverberation, sublimation, fixation, separation, reduction, coagulation, tincture, and the like.'

The significance of Paracelsus in alchemy lies in his vigorous insistence that its true object was to prepare healing drugs and not to make gold. His missionary work in this field gave to alchemy a new orientation and fresh life. Here came at last, after a thousand years, a parting of the ways. A new alchemy, allied with medicine, now arose. Known under the name of iatro-chemistry, or medico-chemistry, it was destined to flourish until about the end of the seventeenth century, while the old alchemy simultaneously fell into a slow decline. This was Paracelsus' greatest service to alchemy; beside it, his introduction of the system of the *tria prima*, or three hypostatical principles (p. 24), and his chemical discoveries were of minor importance.

In medicine, Paracelsus condemned the orthodox system: this made extensive use of herbal remedies, and was based upon the writings of Galen (second century A.D.) and Avicenna, or Ibn Sina (A.D. 980-1037), 'the brightest star of Islamic medicine.' Considering the state of the human organism from a chemical point of view as a regulated conglomeration of the *tria prima* in a condition of flux, Paracelsus held that in disease it needed chemical medicines capable of adjusting the proportions of the *tria prima* or the qualities which they incorporated. With the development of this doctrine, the apothecary changed gradually from a Galenic herbalist into an iatro-chemical or spagyric pharmacist, or compounder of chemical medicines, including such dubious remedies as salts of mercury, lead, arsenic, and copper, together with tinctures of many kinds.

These unorthodox views, urged very often in coarse and vituperative language, naturally aroused the violent opposition of the vested interests under attack, and particularly of the closely knit fraternity of physicians. Matters came to a head at Basel in 1527. As a consequence of certain spectacular cures, Paracelsus was given the dual appointment of city physician and professor at the University. Inspired by Luther's treatment of the Papal Bull at Wittenberg seven years earlier, Paracelsus celebrated his appointment by publicly consigning the venerated writings of Galen and Avicenna to the flames on the Basler market-place. Moreover, he presumed to lecture in German, instead of in Latin, the language of the learned, and to wear the stained garments of the laboratory instead of the opulent and dignified doctoral robes which he had derided. He was expelled from Basel, to lead thenceforward an unsettled and wandering existence as a freelance practitioner of medicine. He died at Salzburg in 1541.

Many of the details of this roving and forceful propagandist, a prophet in medicine and alchemy and at the same time a dabbler in magic, mysticism and astrology, are unknown. His vague ideas, superstitions and diatribes, his self-conceit, overbearing dogmatism and erratic habits, have to be weighed against his lofty vision of the true scope of medicine and the success of his shock tactics in rousing contemporary physicians from their torpidity and in revivifying both medicine and alchemy.

In various portraits (Fig. 25), some of dubious authenticity, he is represented as holding a sword, with one hand resting upon the pommel. This sometimes bears the word 'Azoth,' signifying the Philosopher's Stone, or the 'vital mercury of the philosophers.' According to one tradition, he used the pommel as a container for opium. Like Michael Scot, Roger Bacon, and other early pioneers of science, he gave rise to legends holding him up as nothing more than a magician or necromancer, as in Butler's *Hudibras* (1664), according to which,

> Bombastus kept a devil's bird
> Shut in the pommel of his sword,
> That taught him all the cunning pranks
> Of past and future mountebanks.

Paracelsus has met with much adverse criticism and disparagement; yet in this pioneer of chemical medicine shines something of the genius of that great period of the Renaissance in which he lived.

The Paracelsians

The seed that Paracelsus had sown began to germinate after his death, and among the fruits thereof was strife. Acrimony developed between physicians of the old order and the followers of Paracelsus, who did not hesitate to intensify their master's drastic mineral remedies. These enthusiasts were rebuked notably by Libavius (p. 92), who accepted the validity of chemical remedies but advocated restraint in their application.

The most thorough-going of the earlier Paracelsians was the enigmatic Basil Valentine (p. 93), whose glowing account of the medicinal virtues of antimonial preparations gave much impetus to Paracelsus' advocacy of mineral medicines. Indeed, the affinity between the writings of Paracelsus and Basilius is in some respects so striking that both writers have sometimes been suspected of plagiarism. Here, Paracelsus must be exculpated, for there is much in the Basilian writings that is post-Paracelsian. Paracelsus, like Basilius (p. 93), dwells upon the striking crystalline appearance of metallic antimony: 'the signed star,' wrote Paracelsus, 'is known to none but the sons of the divine Spagyric Art.' Basilius extolled the medicinal virtues of antimonial medicines: 'Although Antimony in its raw state is a deadly poison, yet poison can attract to itself poison more effectively by far than any other heterogeneous substance . . . there is hidden in it [the Star] a wonderful medicine, which also may be prepared from it.'

Basilius also inveighs against the 'wretched and pitiable medicasters' in the true bombastic style of Paracelsus: 'Good God!' he exclaims, in *The Triumphal Chariot of Antimony* (p. 93). 'If an examination were held on these points how many doctors of both branches of medicine would be compelled publicly to declare their ignorance! . . . They do not even trouble to enquire in what way the medicines they prescribe are prepared. . . . They inscribe upon a sheet of paper that magic word *Recipe*, the names of certain medicines, whereupon the Apothecary's assistant takes his mortar, and pounds out of the wretched patient whatever health may still be left in him. . . . Antimony, you affirm, is a poison: therefore let every one beware of using it! But this conclusion is not logical, Sir Doctor, Magister, or Baccalaureas; it is not logical, Sir Doctor, however much you may plume yourself on your red cap. . . . Antimony can be so freed of its poison by our Spagyric Art as to become a most salutary Medicine.'

Basilius continues, in the high Paracelsian vein: 'No one besides myself, has any real acquaintance with its potency, virtues, powers, operation, and efficiency. If any person could be found, he would be worthy to be drawn about in a triumphal car, like great kings and warriors after mighty and heroic achievements in the battlefield. But I am afraid that not many of our Doctors are in danger of being forcibly placed in such a car.'

The enthusiasm for antimony, shown by this supposed

Benedictine monk, led to a joyous apocryphal story concerning the origin of the name 'antimony.' Having noticed that the monasterial hogs waxed fat after devouring his discarded antimonial residues, Basilius surreptitiously introduced some of the material into the fare of his unsuspecting brethren, carefully exempting himself as a control. The effect upon his fellow monks was so unfortunate that the magic metal became known as 'anti-moine,' or 'monk's enemy!'

There was a notable contemporary of Libavius and the pseudonymous Basil Valentine, who, in 1608, sponsored the Paris edition of Sendivogius' *Novum Lumen Chymicum* (p. 87). This Jean Beguin, with the help of several influential Parisian physicians, notably Jean Ribit and Turquet de Mayerne, opened in Paris about the year 1604 a school for the teaching of 'chymistry' (as this transitional form of alchemy now came to be called) and pharmacy. He gave lectures and practical demonstrations dealing with the preparation of chemical medicines, and in 1610 issued for the help of his students a little work entitled *Tyrocinium Chymicum* ('The Chymical Beginner'). A revised and enlarged edition was published in French, at Paris in 1615, under the title *Les Elemens de Chymie* (Fig. 26). This clear exposition of practical methods used in pharmaceutical preparations and of the iatro-chemical or spagyric view of 'chymistry' stands out in sharp contrast to the mystical outpourings of Beguin's contemporary, Count Michael Maier. Indeed, the writings of these two authors afford one of the most telling illustrations of the parting of the ways in alchemy. Beguin's work became the most popular book on 'chymistry' of the seventeenth century; between 1612 and 1690 nearly fifty editions appeared in various languages, mostly in Latin.

There was little of the mystic about Beguin; but this cannot be said of the somewhat later Johannes Baptista van Helmont,[1] as is evident from his remarks upon his

[1] *Humour and Humanism in Chemistry*, Fig. 17.

LES

ELEMENS DE CHYMIE,

DE MAISTRE IEAN BEGVIN AVMOSNIER du Roy.

Seigneur vous m'auez delecté en l'être des choses qu'auez faictes, & me resiouiray és œuures de vos mains. Psal. 91.

A PARIS.

Chez MATHIEV LE MAISTRE, ruë S. Iean de Latran à l'Arbre sec.

Auec priuilege du Roy.

M. DC. XV.

Fig. 26. Title-page of *Les Elemens de Chymie*

alleged transmutation.[1] In some other respects he was remarkably clear-sighted, and although he followed Paracelsus up to a point, yet he disagreed with him concerning the *tria prima*. In fact, he went further and discarded also the four elements of Aristotle, in order to revert to the ideas of the Greek philosopher, Thales (*c.* 600 B.C.), who sought the primordial principle in water. Van Helmont was a good experimentalist. He pointed out that many materials of the plant and animal world, as well as many of mineral origin, yield water when heated. In a celebrated experiment, he grew a small willow tree in earth for five years, supplying it with nothing but water. Allowing for the small loss of weight of the earth in which it grew, he found that the tree had increased in weight from 5 to 169 pounds. Quite justifiably, on the knowledge of the day, he concluded that the substance of the tree had been built up from water alone. Although he (or possibly Paracelsus before him) invented the word *gas* (from 'chaos'), van Helmont had no precise knowledge of gaseous substances, and was unaware of the function or indeed of the presence in the atmosphere, of carbon dioxide, from which, through the processes of plant life, the tree had drawn most of its increase.

Early in the seventeenth century there grew up in Paris, under the original influence of Jean Ribit, Turquet de Mayerne and certain broad-minded associates, mostly Protestants, a group of Paracelsians who became patrons of Jean Beguin. Shortly before Beguin's death there came to Paris, about the year 1618, an Aberdonian bearing the name of Davidson, which he eventually gallicised as d'Avissone. Through Ribit, he became the virtual successor of Beguin, whose tradition he continued. Later, in 1647, Davidson[2] became the first professor of chemistry at the Jardin du Roi in Paris, so that he ranks as one of the earliest, if not the very earliest, of chemistry professors. Until the seventeenth century, chemistry, such as it was,

[1] *Humour and Humanism in Chemistry*, p. 76. [2] *Op. cit.*, Fig. 20.

had been taught by professors of medicine; but in 1609 Johann Hartmann was appointed in the University of Marburg to give public lectures on iatro-chemistry, or medico-chemistry; and in 1639 Werner Rolfinck was installed as 'Director exerciti chymici' in the University of Jena.

Upon his appointment Davidson announced that he intended to 'devote much attention to the preparation and exaltation of antimony, because words are lacking by which to name so rich a substance . . . there is no more lofty medicine under heaven.' There is no doubt that the excessive use of antimonial, mercurial, and other mineral medicines caused much mischief at that time; but Davidson stoutly defended their application. Taking his cue from Paracelsus, he advised physicians who were ignorant of chymistry to keep their mouths shut, since one must know something about the subject before starting to decry it. Pronouncements of this kind brought him into collision with the conservative medical fraternity of Paris; and as a foreigner and a heretic, both in religion and medicine, Davidson was forced to resign his post in 1651.

Davidson's lectures on chymistry, delivered in Latin, were devoted mainly to the preparation and uses of medicinal chemicals, with an explanation of the processes and apparatus concerned, and accompanied by practical demonstrations. After Davidson's day, a demonstrator was provided for this latter purpose, one of the most notable of them in the following century being Guillaume-François Rouelle, the teacher of Lavoisier (p. 139). For some two hundred years after the foundation of the chair of chemistry at the Jardin du Roi, the progress of chemistry in France was closely bound up with the work of the many eminent chemists who worked in this institution as professor or demonstrator of the subject: among them were Glaser, Bourdelain, the brothers Rouelle, Macquer, Gay-Lussac and Chevreul.

A charming engraving (Fig. **27**) of 1676 shows 'la leçon de chimie au Jardin royal' at that time. The professor is seated at a table, with an open book before him, a bottle in his right hand, and a bundle of dried herbs at his feet. The members of his class are adults, wearing the picturesque cloaks and broad-brimmed hats of the period; some of them are seated, while others stand around the table. A secretary, in a seat facing the professor, takes notes. A laborant attends to a furnace, and another works at a bench below a window looking out upon the gardens. The display of contemporary apparatus shown at the back of the room includes a 'serpent,' used in rectifying spirit of wine, and described by Davidson's successor, Nicasius le Febure, as 'a Vessel to alkolize the Spirit of Wyn in the very first distillation.' There is also a large glass-fronted recess containing numerous pharmaceutical specimens.

This Nicasius le Febure, or Nicholas le Fèvre, like Beguin and Davidson, had also given public lectures and demonstrations in Paris on spagyric chemistry. After serving for nearly ten years at the Jardin du Roi he became 'Royal Professor in Chymistry' to Charles II in 1660, soon after the Restoration. His *Traicté de la Chymie*, published at Paris in 1660, achieved wide recognition as a standard treatise on chemistry for the next hundred years. It ran through many editions in several languages; the first English edition was issued in 1661 under the title, *A Compleat Body of Chymistry*. It was not written in Latin because le Febure addressed it 'not only to the Apothecaries, but likewise to men of other professions.' It embodied the fruits of an experience of some thirty-five years in preparing pharmaceutical remedies from vegetable, animal, and mineral sources. Chymistry, according to le Febure, was tripartite: Philosophical, or wholly Scientifical; Iatrochymy, or Medicinal Chymistry which depends upon the first kind; and Pharmaceutical Chymistry, belonging to the Apothecary's profession, which depends upon the second kind. In essence, the book is a compendium of medicinal preparations, clearly described according to the technique of the period. There are many copperplate engravings of apparatus and processes with admirable annotations and descriptions.

Charles II took much interest in le Febure's laboratory at St. James's Palace. In 1662 he took John Evelyn to see it and to meet, as Evelyn wrote in his Diary, 'Monsieur Lefevre, his chemist (and who had been my master in Paris), to see his accurate preparation for the composing Sir Walter Ralegh's rare cordial: he made a learned discourse before his Majesty in French on each ingredient.' Samuel Pepys also records in his famous Diary that he paid a visit in 1669 to 'the King's little elaboratory, under his closet [study], a pretty place; and there saw a great many chemical glasses[1] and things, but understood none of them.'

Christophle Glaser, who succeeded le Febure at the Jardin du Roi, also published a successful *Traité de la Chymie* in 1663, which appeared in English under the title, *The Compleat Chymist* (1677), and also in German.

The works of Beguin, le Febure, and Glaser, successful as they all became, were completely outstripped in popularity by the *Cours de Chymie* of Nicolas Lemery. First published in 1675, this book was issued in numerous editions in various languages, and became the most widely read of all expositions of chemistry until the second half of the eighteenth century. The first of four English editions, entitled *A Course of Chymistry*, was published in 1677. Lemery was for a time a pupil of Glaser, and his original *Cours de Chymie* owed a considerable debt, unacknowledged, to Glaser's excellent *Traité*.

Of the same general character as its immediate predecessors, Lemery's book was more interestingly written, in a clear and attractive style. He was a skilled practicant, and his directions, sensibly indebted to his own work, were notably precise. An extensive index gave the reader quick access not only to such directions but likewise to a long list of remedies for almost every conceivable human ill, ranging

[1] *Humour and Humanism in Chemistry*, Fig. 31.

from toothache and corns to palpitations and 'hypochondriack melancholy.' For madness, powder of vipers might be tried; for deafness, oil of paper 'dropt in the Ear' is recommended. Also, if Lemery can be believed, hysterical women can be commonly relieved by the disagreeable smell of burning paper.

At the opening of his account of gold, Lemery gives an interesting and spirited account of the transmutationists and seekers after the Philosopher's Stone, thereby intimating that adherents of the old alchemy were still active at that time. He speaks of 'the labours, and pains, watchings, vexations and frettings,' of the 'puffer' type of alchemist; of their operations and materials; of their many trickeries and 'subtle inventions, by which they too often impose on such as have plenty of mony, to make them become fellow-partners with them in their Operations.' He concludes by saying that 'to spend one's time in making of *Gold*, seems properly to lose it by working in the dark, and I find that *Alchymy* has been very well defined to be, *Ars sine arte*, *cujus principium mentiri*, *medium laborare*, *& finis mendicare*, an Art without any Art, whose beginning is Lying, whose middle is nothing but Labour, and whose end is Beggery.'

Quite as impatient with alchemical mysticism as with the delusions of the 'puffers,' Lemery held independent views on chemical theory. He acknowledged that 'some prejudiced *Chymist*' might complain that he did not season his explanations 'with *Salt* enough, and *Sulphur*.' He tried in places to correlate the properties of substances with the imagined shapes of their ultimate particles, in a kind of embryonic atomic view of matter. He recognised the limitations of knowledge and the great obstacle of mental rigidity: 'The life of Man is too short to try all,' he wrote. 'Men mind only what is most necessary and love to follow the common road of others.'

Although some of the iatro-chemists were men of moderate views, there were others who carried the Paracelsian doctrines to excessive lengths; so that eventually, towards the end of the seventeenth century, iatro-chemistry fell into discredit and began to decline. One of its extremists, de la Boë (Dubois) Sylvius, depicted medicine as little more than chemistry applied to a machine. He ascribed diseases to the presence of an acid or an alkaline 'acridity,' and looked upon the processes of the body, whether in health or disease, as purely chemical. Guided by such views, he did not hesitate to prescribe dangerous internal medicines, such as zinc sulphate and silver nitrate. In his *History of Chemistry* (1830), Thomas Thomson wrote that in the human body Sylvius 'saw nothing but a magma of humours continually in fermentation, distillation, effervescence, or precipitation; and the physician was degraded by him to the rank of a distiller or brewer.'

Continuation of the Practical Tradition

The iatro-chemists rendered a great service to chemistry by keeping alive its practical tradition in the sixteenth and seventeenth centuries. In this respect they took over the task which had fallen in the medieval period to the metal workers and other kinds of craftsmen and artificers (p. 89). Their enthusiasm for chemical preparations led to advances in practical technique and to a number of discoveries of new substances; while their intelligible text-books, free for the most part from the mysticism and obscure expression of alchemy, gave a wide publicity to the nature and importance of chemistry. On the other hand, the iatro-chemists had little interest in chemical theory, and were quite content, in the words of Lemery, 'to follow the common road of others,' which amounted to the continued acceptance of the four elements and the *tria prima*.

Curiously enough, the greatest worker of the seventeenth century in practical chemistry, Johann Rudolph Glauber (1604-70), has little claim to be enrolled among the iatro-chemists. He was essentially an enthusiastic research chemist, with a burning desire to advance the frontiers of chemical knowledge. Owing to the absence of any useful underlying theory, he was unable to work to a plan; nevertheless he made many disconnected discoveries of great importance in qualitative (p. 6) chemistry. He seems to have been attracted to chemistry in a romantic way, as the result of his relief from a fever through the medicinal virtue of a natural mineral water. This he afterwards affirmed to contain the wonderful 'Glauber's salt,' or *sal mirabile* (sodium sulphate), which he regarded as a universal remedy, little inferior to the *Elixir vitae*.

Like Paracelsus, Glauber was of a restless disposition; and since most of his researches were carried out amidst the disturbances of the Thirty Years' War, it is astonishing that he was able to accomplish so much original work and to add to it an extraordinary literary output. Between 1648 and 1660 he wrote about thirty treatises in German, with Latin titles. A collected edition of his writings, *Opera Omnia*, first published at Amsterdam in 1661, was issued in an English translation by Christopher Packe in 1689, in a large folio volume of some 750 pages, with illustrations printed from Glauber's original copperplates. This work partakes of the nature of an early encyclopaedia of pure and applied chemistry. It shows that Glauber, while possessing great experimental skill and keen observation, was imbued with the beliefs and superstitions of the old alchemy. He discovered many new substances, among them his beloved sodium sulphate, also 'butter of arsenic' (arsenic trichloride) and potassium acetate; he introduced improved methods for preparing various mineral acids and salts; and he noticed the formation of a number of gaseous substances, although he had no technique at his command for collecting or examining them. He distilled both wood and coal from a brick oven and collected the volatile products as well as he could, by passing them through an air-cooled earthen channel or pipe. In this way, he was the first to prepare crude coal-tar distillates, which he did so early as 1648.

Glauber had a shrewd appreciation of the economic and

Fig. 28. Robert Boyle, 1627–1691

(*See p. 112*)

Fig. 30. (*above*) A Laboratory fo[r] Practical Chymistry in 1747

(*See p. 125*)

Fig. 33. Monument at Stockhol[m] to Carl Wilhelm Scheele, 1742–17[86]

(*See p. 133*)

applied aspects of chemistry. Thus, he used wood tar to repel insects 'which are wont to damnifie Fruit,' and made use of linseed oil, which had been boiled with a drier, in waterproofing cloth. He even applied one of his unsuccessful transmuting tinctures to his bald head, which, as he wrote, 'began to be cover'd with black curl'd hairs, from which I am verily perswaded, that had I more of the like Tincture, it would have wholly renewed me.' In his last years Glauber's health was seriously affected through his exposure to toxic compounds of mercury, arsenic, and antimony; but his enthusiasm for chemistry remained undimmed, although his work brought him no reward in an age which had no use for a research chemist not holding a recognised position or possessing a wealthy patron. In Glauber's own words, 'by all that ever I writ I never gained one halfpeny.' After a life's devotion to the cause of chemistry he died in poverty.

'*Wholly Scientifical Chymistry*'

The 'chymical artists' of the seventeenth century were essentially practical workers, with little interest in theory. Their theoretical views, in so far as they concerned themselves with such superfluities, were easily reconciled with the current notions. Their numerous distillations of plant and animal materials gave them phlegm and oil (aqueous and oily distillates), salt (sublimed matter), earth (residue), and spirit or air (vapour or gas); and these products were easily fitted into the pattern of the Aristotelian quartette and the Paracelsian *tria prima*.

As mentioned above (p. 106), le Febure recognised that both 'pharmaceutical chymistry' and 'iatrochymy' were dependent in the end upon 'philosophical, or wholly scientifical chymistry.' In retrospect, however, it is clear that no significant change in pure chemistry (as we should now call it) was possible under the aegis of the stagnant and time-worn theories of the four elements and the *tria prima*. These barren conceptions offered no inspiration for an advance; but at long last a new era began to dawn with the critical views and practical work of Robert Boyle (Fig. **28**) in the early years of the second half of the seventeenth century.

The Honourable Robert Boyle (1627-91), was the seventh son and fourteenth child of Richard Boyle, the celebrated Earl of Cork. A man whose great nobility of character shone as a beacon-light in the dark and dissolute age of Charles II, Robert Boyle was fortunate in possessing both the means and the inclination to devote his life to study and scientific research. These researches ranged over a wide field, particularly in the domain of physics. Through his experiments on the 'spring of air' his name is perpetuated in the famous Boyle's Law, according to which the volume of a gas varies inversely as the pressure to which it is subjected; but in spite of this and many other researches of a physical nature, Boyle confessed himself 'a great Lover of Chymical Experiments,' and it was in chemistry that he found his greatest satisfaction.

Boyle was the first eminent exponent of Francis Bacon's inductive system of philosophy, based on experiment, observation, and measurement, as expounded in his *Novum Organum* (1620). Boyle realised that chemistry must take its place as an independent branch of natural philosophy, and not as an adjunct to the medically minded iatro-chemists or the gold-seeking alchemists. Nevertheless, like Newton, he believed in the possibility of transmutation of metals, although evidently not as a profitable source of the noble metals, seeing that in 1689 he was active in obtaining the repeal of a medieval English statute which prohibited the multiplying of silver or gold.

Among his numerous chemical investigations Boyle noticed that various metals, among them tin, lead, and copper, underwent an increase in weight when heated in air. He ascribed this result erroneously to the absorption by the metal of heat, which he viewed as 'ponderable,' that is, as consisting of material 'igneous particles' possessing weight. He also formed rational ideas concerning chemical reactions and chemical analysis.

Boyle's greatest service to chemistry, however, lay in the field of theoretical conceptions. In his celebrated book, *The Sceptical Chymist: or Chymico-physical Doubts and Paradoxes* (1661) he brought his powers of clear thinking and logical deduction into full play against the entrenched ideas of the Aristotelian 'elements' and the Paracelsian 'principles.' In the course of a critical and trenchant argument he stated that 'the Experiments wont to be brought, whether by the common Peripateticks [Aristotelians], or by the vulgar Chymists [iatro-chemists], to demonstrate that all mixed bodies [compounds] are made up precisely either of the four Elements, or the three Hypostatical Principles, do not evince what they are alledg'd to prove.'

Boyle then went on to advance for the first time what is essentially the modern conception of an element, which he visualised as a substance which cannot be split up into simpler ones. 'I now mean by Elements,' he wrote, 'as those Chymists that speak plainest do by their Principles, certain Primitive and simple, or perfectly unmingled bodies; which not being made of any other bodies, or of one another, are the Ingredients of which all those call'd perfectly mixt Bodies are immediately compounded, and into which they are ultimately resolved.' It was more than a hundred years later that Lavoisier devised experimental means of recognising elements.

In a later publication Boyle took the iatro-chemists particularly to task for the persistent lack of clarity in their writings. He pointed out 'in how Laxe, Indefinite, and almost Arbitrary Senses they employ the Terms of *Salt*, *Sulphur* and *Mercury*; of which,' he continued, 'I could never find that they were agreed upon any certain Definitions or setled Notions; not onely differing Authors, but not unfrequently one and the same, and perhaps in the same Book, employing them in very differing senses.' In this respect the iatro-chemists were but following the traditions of alchemy. Since they had no precise conception of chemical theory, they could not be expected to express their vague notions in precise language.

Boyle had laid an axe to the root of the tree of Aristotle and Paracelsus; but it was a still shrewder blow from Lavoisier that brought this ancient growth, together with its later phlogistic entanglements, crashing to the ground towards the end of the eighteenth century.

Boyle's experimental work in chemistry did not consist of a string of haphazard operations, like that of his predecessors. He worked to a plan, directed towards the solution of a definite problem. He did not, of course, always arrive at the correct interpretation of his observations. Notably, he attributed the increase of weight in his experiments on the calcination (heating in air) of metals to their absorption of igneous particles, as mentioned above; so that he viewed the resulting calx (oxide) as a compound of the metal with fire. Here, he had fastened his attention upon a problem of the very first importance in chemistry, namely, the chemical nature of combustion, or burning.

Two of Boyle's contemporaries, Hooke and Mayow, also addressed themselves to this problem. Robert Hooke (1635-1703), a great scientific genius, was at one time assistant to Boyle. His work was mainly of a physical and mechanical nature: his inventions were of an extraordinary range and fertility. He paid little attention to chemistry in his published work; but in his *Micrographia* (1665), a pioneer work of much beauty on microscopical anatomy, he made some casual references to combustion, which, if he had been able to develop them, might well have changed the course of chemistry throughout the ensuing eighteenth century.

Here are some of Hooke's pregnant remarks, recorded in his *Micrographia*: 'Air is the *menstruum* or universal dissolvent of all *sulphureous* [combustible] bodies. . . . *The dissolution* of sulphureous bodies is made by a substance inherent, and mixt with the Air, that is like, if not the very same, with that which is fixt in *Salt-peter*. . . . *In this dissolution* of bodies by the Air, a certain part is united and mixt, or dissolv'd and turn'd into the Air, and made to fly up and down with it. . . . The dissolving parts of the Air are but few . . . and therefore a small parcel of it is quickly glutted, and will dissolve no more. . . . There is no such thing as an Element of Fire. . . . That shining and transient body which we call *Flame*, is nothing else but a mixture of Air, and volatil sulphureous parts of dissoluble or combustible bodies.' In the light of later knowledge it is easy to interpret too generously the scientific statements of an earlier age. Hooke stood on the verge of the truth; although it must be added that he could not have established it experimentally without a knowledge of the technique of isolating and manipulating gases. This knowledge, after having been gained and applied by others, ultimately led Lavoisier to a solution of the problem. Meanwhile another century had passed away: 'Science moves, but slowly slowly, creeping on from point to point,' wrote Tennyson in a still later century.

A planned attack upon the same fundamental problem was made soon after Hooke's publication by John Mayow (1641-79), a young Cornishman who practised medicine at Bath and devoted his leisure hours to chemical research, concerned mainly with combustion and respiration. Mayow, like Hooke, perceived a similarity between burning in air and combustion, or deflagration, with saltpetre. In his eyes both air and saltpetre contained a so-called 'nitro-aërial spirit,' supporting combustion (1674). He attributed the increase in weight attending the calcination of a metal to the absorption of nitro-aërial particles from the atmosphere. Moreover, he attributed to a similar cause the decrease in volume of a limited quantity of air during the burning in it of a candle, or of a piece of camphor, fired by means of a burning glass as shown in Fig. 29. In another experiment he replaced the candle by a live mouse (Fig. 29) and noticed that a similar contraction attended the process of animal respiration. In these experiments Mayow devised clever extensions of the method, already known, of confining the air under examination in glass vessels inverted over water. His work confirmed and stressed earlier observations showing that a confined volume of air contracts during the process of combustion in it, and also that the residual air is incapable of supporting life.

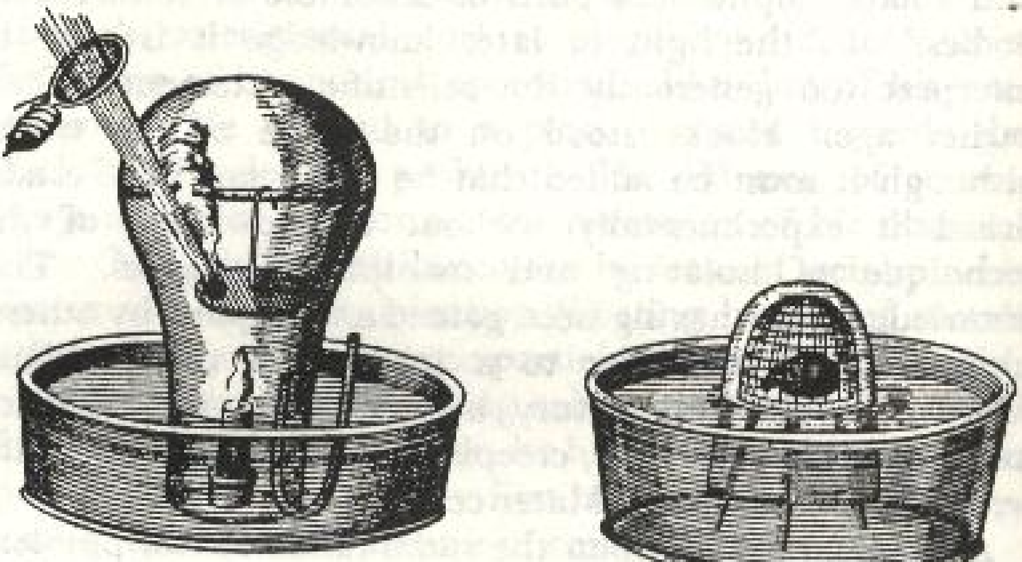


Fig. 29. Mayow's Apparatus

Like Hooke, Mayow trembled on the brink of a great discovery; which, however, again like Hooke, he was unable to bring to fruition owing to his rudimentary ideas concerning gases and their manipulation. His nitro-aërial spirit, unlike the oxygen of Lavoisier, was not conceived as a gaseous component of the atmosphere; the presence of nitro-aërial particles was postulated, for example, in the sun's rays. Neither Mayow, nor Hooke, nor any other investigator for more than a hundred years, was able to formulate the fundamental conception of the air as a mixture of gases. Until the imagination, stimulated by further experimental evidence, was able to give birth to that conception, late in the following century, chemistry—despite the brilliant work and ideas of Boyle, Hooke, and Mayow—remained in a state of suspended animation.

VIII · THE SWAN SONG OF ALCHEMY

Chemistry and the Scientific Revolution

THE dawn of the seventeenth century brought with it the dawn of the 'scientific revolution,' and thereby heralded the birth of modern science. The scientific revolution of the seventeenth century hinged upon astronomy, the oldest of the sciences, and found its inspiration in the law of inertia. The ideas of Galileo (1564-1642) concerning mass and inertia formed the foundation of the first law of motion, as enunciated by Newton (1642-1727), who was born in the year of Galileo's death. According to this law, every body continues in its state of rest or of uniform motion in a straight line, except in so far as it is compelled by impressed force to change that state. Thus, nearly a century and a half after Copernicus had published his great work *De Revolutionibus Orbium Coelestium* (1543), Newton was able in his *Principia* (1687) to effect his grand synthesis of the fundamental dynamical and gravitational problems concerned in the motions of the heavenly bodies. This correlation of dynamics and astronomy, of motion on the earth and in the skies, of the falling apple and the falling moon, lies at the very core of the scientific revolution of the seventeenth century.

Similarly, in another vastly removed field of science, Vesalius' master-work of anatomy, *De Fabrica* (1543), was followed in due course by William Harvey's revolutionary work, *De motu cordis* (1628), dealing with his discovery of the circulation of the blood. A new era had opened also in the study of living organisms.

The scientific view of these enormous advances represents only one aspect of the scientific revolution. That revolution had a much wider significance. The new scientific conception of a macrocosm subject to dynamical laws and no longer impelled in its motions by invisible hands, and the new knowledge of the living microcosm of man, exerted a profound influence upon the society and general mental attitude of the day. Here is an example of the truism, so important and yet so often overlooked, that the history of science does not exist as an immiscible layer, floating upon the stream of general history; but that it is an all-pervading and vivifying ingredient of that stream.

From what has been said above, it is clear that the scientific revolution of the seventeenth century failed to reach chemistry, which pursued a placid and uneventful course throughout the century, enlivened only by the ideas and experiments of Boyle, Hooke, and Mayow in its later half. In seeking to explain the lag in the progress of chemistry, it must be borne in mind that this science has its fundamental basis in obscure principles, the elucidation and appreciation of which called for prolonged speculation and experiment.

Looking back to the position of chemical science at the opening of the eighteenth century, it is now apparent that before chemistry could divest itself of the hardened accretions of alchemy there were certain fundamental issues to be resolved. Chief among them were: first, the nature of a chemical element; secondly, the nature of chemical composition and chemical change, especially of burning or combustion, and of the so-called element, fire; thirdly, the chemical nature of the so-called elements, air and water.

Boyle had thrown some light upon the nature of an element, without establishing any experimental method of diagnosis. He had also developed some simple methods of chemical analysis, including the use of certain plant juices in testing for acids, bases, and salts. He had, however, come to a wrong conclusion in trying to explain the increase of weight attending the calcination of tin and other metals. Hooke had made a contribution to ideas concerning the nature of combustion and of flame. The contemporary iatro-chemist, Tachenius, like Boyle, had shown some knowledge of chemical reactions and tests, including notably the application of tincture of galls as a reagent for certain metallic salts in solution. In spite of these advances the chemical nature of the Aristotelian elements, air, fire, and water, remained a complete enigma.

These great unsolved problems could not be elucidated by processes of pure thought. They called for the application of systematic experiments—logical questions put to Nature—followed by accurate observation and intelligent interpretation. That is the scientific method in a nutshell. It is true that by processes of pure thought Democritus and others arrived at atomistic ideas in ancient Greece; but these ideas stagnated for more than two thousand years as nothing better than idle speculations. It is only with accurate experiment and observation to work upon that imagination can become the architect of scientific theory.

It is certainly a great tribute to the Aristotelian scheme that three of its so-called elements figure in the above list of obstacles that blocked a break-through from alchemy to chemistry in the eighteenth century, more than three thousand years after the idea of the four elements was conceived in India and Egypt.

Why was the nature of combustion so important? . . . First, because it is the most spectacular and fundamental of all familiar chemical processes. Secondly, it is a process which concerns all four of the Aristotelian elements. A piece of wood burns: *air* is necessary; *fire* is produced; *water* is an important product of the burning; *earth* (ashes) is left. Thirdly, there is the literally 'vital' importance of combustion; for it is a slow and regulated combustion that maintains animal heat in the metabolic processes upon which animal life depends. The alchemists looked upon air as 'the food of fire'; it is equally 'the food of living organisms,' both plant and animal.

The Theory of Phlogiston

It was essentially lack of knowledge of gases and the experimental technique of isolating and handling them that gave to chemical theory a wrong direction at the opening of the eighteenth century, when Stahl (1660-1734), in his *Zymotechnia Fundamentalis*, published in 1697, advanced views on combustion which became known as the 'Theory of Phlogiston.' Stahl's views were based in turn upon ideas which Becher (1635–82) had put forward much earlier, in 1669, in his book *Physicae Subterraneae*.

Becher held all minerals to be composed of three constituents, which he named *terra pinguis*, *terra mercurialis*, and *terra lapida*. These were essentially the sulphur, mercury, and salt of the *tria prima* under a thin disguise. Becher supposed that all combustible matter lost the *terra pinguis*, or combustible principle, during the process of burning. 'Metals contain an inflammable principle,' he said, 'which by the action of fire goes off into the air'; and he regarded the resulting metal calces (oxides) as composed of *terra lapida* and *terra mercurialis*.

Stahl, in turn, gave a new name to the imagined *materia ignis*, or inflammable principle, of combustible bodies: he called it phlogiston (Greek, *phlogistos*, burnt, inflammable). Metals thus became compounds of their specific calces with a common phlogiston. Carbon, being rich in phlogiston, could restore the phlogiston to a calx, when heated with it, and thus regenerate the metal; but in point of fact, as we now know, instead of adding phlogiston, the carbon takes away oxygen from the calx. In brief, phlogistic thought gave a negative interpretation of a positive process: when a metal is calcined it does not lose phlogiston; it gains oxygen. Air, too, was regarded as a passive or negative agent in combustion—as a receiver of phlogiston from the burning body, rather than as a giver of oxygen to it; so that air which had become vitiated by combustion was held to be saturated with phlogiston, instead of deprived of oxygen, and was accordingly called 'phlogisticated air' (nitrogen).

From a backward historical glance it is clear that the idea implicit in phlogiston was almost as old as alchemy itself. Becher's *terra pinguis*, or 'fat earth,' was a revival of Paracelsus' statement that 'the life of metals is a secret fatnesse, which they have received from sulphur'; much earlier still, Geber defined sulphur as *pinguedo terrae*, or 'fatness of the earth'; and Geber's positive Sulphur and negative Mercury were derived in turn from the Sun and Moon of the Emerald Table of Hermes, and so from the Sun-god and Moon-goddess of the ancient religions, and even still more remotely from the Doctrine of the Two Contraries (p. 2).

It was the retrograde nature of Stahl's theory that led the American historian of alchemy, A. J. Hopkins, to bestow upon the era of phlogiston the fitting and picturesque title of 'the swan song of alchemy.'

From the very outset the theory was clearly inadequate, for it ignored two well established facts: first, that metals undergo an increase (instead of a loss) of weight when calcined; secondly, that a confined volume of air contracts (instead of expanding) when a body is burnt in it. The fact that tin increases in weight when heated in air had indeed been recorded by Jean Rey in 1630, five years before Becher's birth. A scientific theory ignoring such patent facts would not hold credence for a moment at the present day. Of the theory of phlogiston the best that can be said is that in this interregnum between alchemy and chemistry a bad theory was perhaps better than none. Although to a limited extent Stahl's theory co-ordinated a number of observations which might otherwise have remained disconnected, yet the important experimental discoveries of this period were made despite the theory, rather than because of it.

In the course of the 'age of reason' of the eighteenth century, the advocates of this 'theory of unreason' were driven to amusing devices in order to provide *ad hoc* explanations for the many demands made upon the theory. The increase of weight of a metal upon calcination was set aside by the airy assumption that phlogiston was a principle of levity possessing negative weight. Alternatively, it could be pictured by those with adventurous imaginations as flying about in the interstices of the metal like a bird in a cage, and therefore exerting no weight until it fell 'dead' during calcination!

Few theories have received such a succession of punishing blows as those with which Lavoisier gave phlogiston its quietus towards the end of the century: 'Chemists,' he said, 'have turned phlogiston into a vague principle which consequently adapts itself to all the explanations for which it may be required. Sometimes this principle has weight and sometimes it has not; sometimes it is free fire and sometimes it is fire combined with the earthly element; sometimes it passes through the pores of vessels, sometimes these are impervious to it; it explains both causticity and non-causticity, transparency and opacity, colours and their absence. It is a veritable Proteus, changing in form at each instant.'

The fundamental mistake of the phlogistians was that they confused the *property* of combustibility with a supposed material *substance*. Their ideas bear the imprint of iatrochemistry, which was concerned so largely with the decomposition by heat of products of plant and animal life, now known as organic matter. The theory afforded a plausible explanation of the burning of organic materials and also of sulphur; for here the loss of weight was apparent (owing to the impossibility, at that time, of collecting the gaseous products of combustion). Indeed, the fiery jets of burning gas streaming from wood and coal might well have suggested the idea of an escape of phlogiston from such burning bodies; but whereas burning wood and coal dwindle to a light ash, metals show an increase in weight when heated in air, because the product is solid and does not escape and lose itself in the surrounding atmosphere.

In trying to unravel the meaning of the clumsy phlogistic terminology, it is sometimes helpful to bear in mind that up to a point the hypothetical phlogiston may be considered as a kind of antithesis of oxygen. That is why, for example, Priestley bestowed the name 'dephlogisticated air' upon the gas which Lavoisier later called 'oxygen'; and why both Priestley and Scheele identified hydrogen with phlogiston itself.

The Earlier Period of Phlogiston

It cannot be said that the theory of phlogiston afforded much inspiration to Hales or Boerhaave, those two outstanding figures in the chemistry of the period between 1700 and 1750. The work of the Rev. Stephen Hales, minister of Teddington in Middlesex, is noteworthy as marking an advance in the study of gases, a field of research which was to become of the first importance in the second half of the eighteenth century. It was perhaps Paracelsus who introduced the word *gas* (p. 104); but van Helmont certainly used it in 1630 in order to describe those mysterious 'wild spirits' which could neither be seen nor kept in vessels. He also drew a distinction between *gas carbonum* from burning charcoal, *gas sylvester* from fermentation, and inflammable *gas pingue*, often produced in the putrefaction and distillation of plant and animal materials.

Boyle advanced beyond van Helmont, in 1660, by actually collecting an inflammable 'factitious air' (hydrogen) in a glass bottle, which he did by putting iron nails into the bottle, filling it with dilute oil of vitriol, and inverting it in a dish containing more of this liquid. A few years later Mayow improved upon this technique of handling a gas, as already explained (p. 116). Hales, as he described in his *Vegetable Staticks* (1727), decomposed many organic and mineral (inorganic) materials by heating them in an iron retort, made of a musket barrel, and allowing the resulting gas to pass out through a pipe which delivered it into a water-filled glass jar inverted over a large vessel containing more water. This apparatus was a forerunner of the pneumatic trough invented by Priestley (Fig. **35**). In these experiments Hales undoubtedly collected impure specimens of carbon dioxide, coal gas, oxygen, hydrogen, and nitric oxide. He regarded them all as 'true air and not a mere flatulent vapour,' because they appeared to have the same specific gravity and elasticity.

The most famous chemist of this period was certainly Herman Boerhaave (1668-1738), one of the thirteen children of the village pastor of Voorhout, near Leyden: he has been described as 'the most distinguished teacher of his time, and a man of immense and varied learning in languages, philosophy, theology, mathematics, botany, chemistry, anatomy, and medicine.' From 1718 onwards he held simultaneously the chairs of medicine, botany, and chemistry in the University of Leyden. His influence upon chemistry was exerted through his teaching, pupils, and writings, rather than his researches. In medicine, he was the first great exponent of clinical teaching, and through him the Leyden School of medicine rose to be the first in Europe.

Boerhaave's pupils and their successors, including Cullen, Black, and Roebuck, were largely responsible for the development of both pure and applied chemistry in Scotland and later in America (p. 129). His massive work, *Elementa Chemiae*, published at Leyden in 1732, was translated into English, French, and German, and became the standard text-book of chemistry until the time of Lavoisier, towards the end of the century. Boerhaave was the last chemist of note who wrote and lectured habitually in Latin.

Boerhaave[1] consistently pursued an independent course, and in chemistry he made no reference to the theory of phlogiston. He held, however, a similar negative view; for he considered that combustible bodies contain a combustible ingredient, not always the same, which he called

[1] *Humour and Humanism in Chemistry*, Fig. **36**.

the *pabulum ignis*, allied with an incombustible ingredient. Thus, Boerhaave supposed sulphur to consist of a combustible oily ingredient, or *oleum*, allied with an incombustible acid. He defined the *pabulum ignis* as 'a matter feeding fire, and converted by the same into the very substance of elementary fire.' He tried to isolate it from concentrated alcohol, which he had treated with 'dried alcaline salt of tartar' (heated potassium carbonate) until it was 'impossible by any further art to procure the least drop more' of water from it. Upon igniting some of this alcohol in a suitable vessel he noticed that the thin fume ascending through the orifice extinguished the flame of a candle, and that water condensed within the vessel. 'How great was my disappointment!' he exclaimed. 'The pabulum of fire, consumed by it, leaves water; and itself becomes so light as to dissipate into the chaos of air, and thus eludes all further pursuit.'

This last remark is full of significance, especially when taken in conjunction with Boerhaave's comment: 'this shews us some fix'd limits of science.' This was a true saying at that day; for without a further knowledge of gases no advance was possible.

Boerhaave's treatment of the theory and practice of chemistry, as expounded in his comprehensive *Elementa Chemiae*, and notably his conception of chemistry as an independent science, brought real chemistry for the first time into the text-books. At the same time, in this first half of the eighteenth century, a marked change had come over chemical laboratories, now turning from the practices and usages of alchemy and iatro-chemistry to those of chemistry. This change is shown clearly by comparing an illustration (Fig. **30**) of a chemical laboratory of 1747 with the representations of Stradanus, Teniers, and their contemporaries. This later laboratory, still showing a pharmacy beyond, is characterised by its orderly character and the variety of large units of equipment set up for specific purposes, such as the 'serpent,' with its long zigzag fractionating column for distilling rectified alcohol from fermented liquors. One of the books lying on the shelf bears the name 'Boerhaave.'

Boerhaave has been described as a man of 'a kindly heart and a keen desire to expound his knowledge to his student following.' He became very wealthy, but persisted in wearing shabby clothes, an old hat, and clumsy shoes. His letters to one of his favourite students, Cox Macro, have been described as 'couched in terms of sincere friendship, but almost exaggerated humility when we reflect that Boerhaave was one to whom "princes, kings, nay emperors themselves, came for medical advice." They show Boerhaave in his usual attractive light, upholding his motto, *Simplex sigillum veri*.'

Forerunners of a New Age

A great change came over the chemical scene in the second half of the eighteenth century. Quiescence and stagnation gave way to activity and spectacular advances heralding the approach of a new age. Of the many actors in this scene, five may be selected as playing leading parts. These five demonstrate the international character of science: for one was a Scotsman; one was a Swede; two were Englishmen; and as the curtain fell, a Frenchman occupied the middle of the stage.

Joseph Black (1728-99) was born at about the time that the erudite Herman Boerhaave, after seeking in vain to isolate the *pabulum ignis*, concluded that his failure 'shews us some fix'd limits of science.' Joseph Black was destined to become the pioneer who first passed beyond those limits, thereby opening a way into the spacious realms of modern chemistry. As a student of medicine at the University of Glasgow, Black came in 1746 under the influence of Dr. William Cullen, who has been described as the first in Great Britain to raise the science of chemistry to its full dignity. After taking his M.D. degree in the University of Edinburgh, Black succeeded Cullen as lecturer in

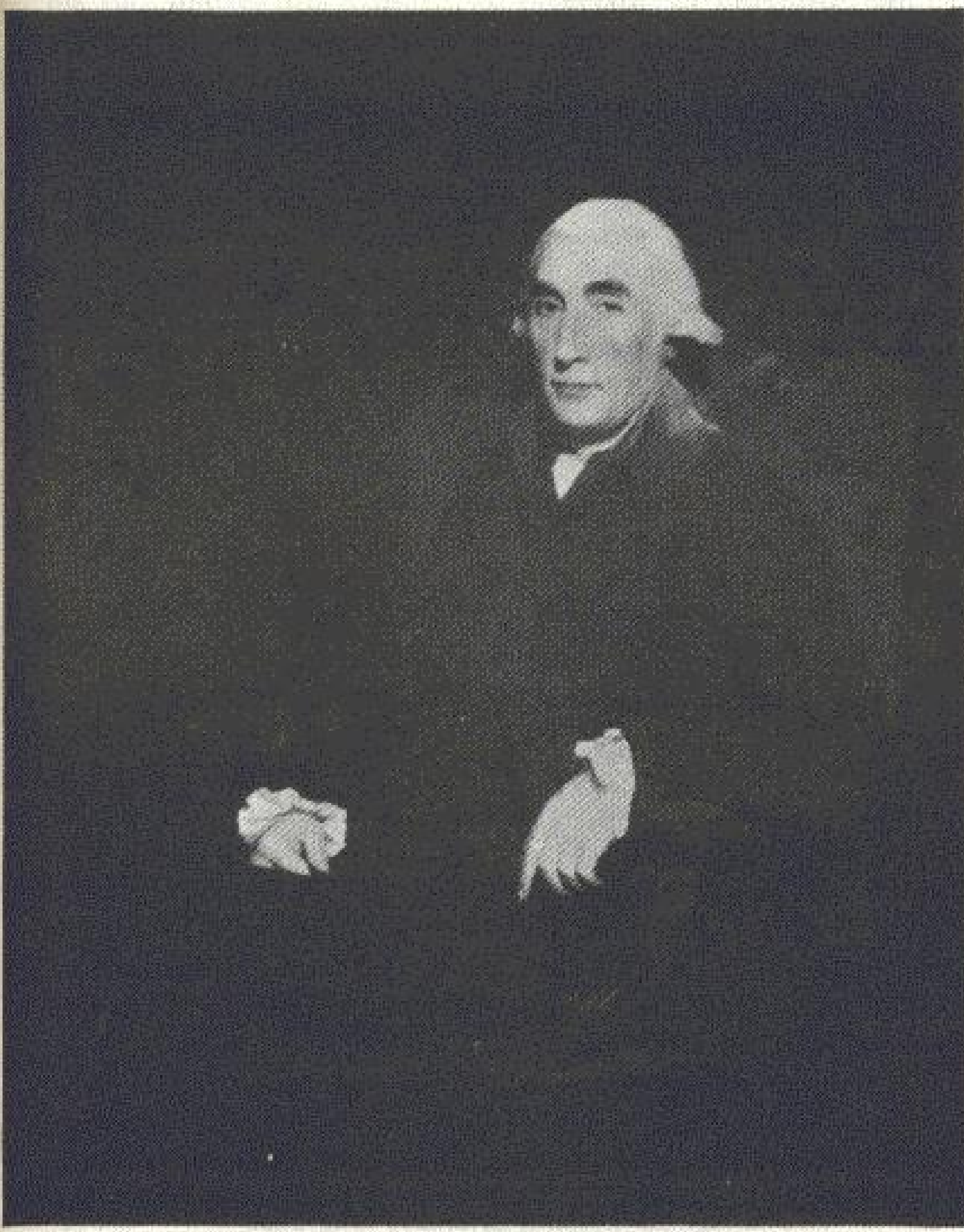


Fig. 31. Joseph Black, 1728–1799

(*See p. 128*)

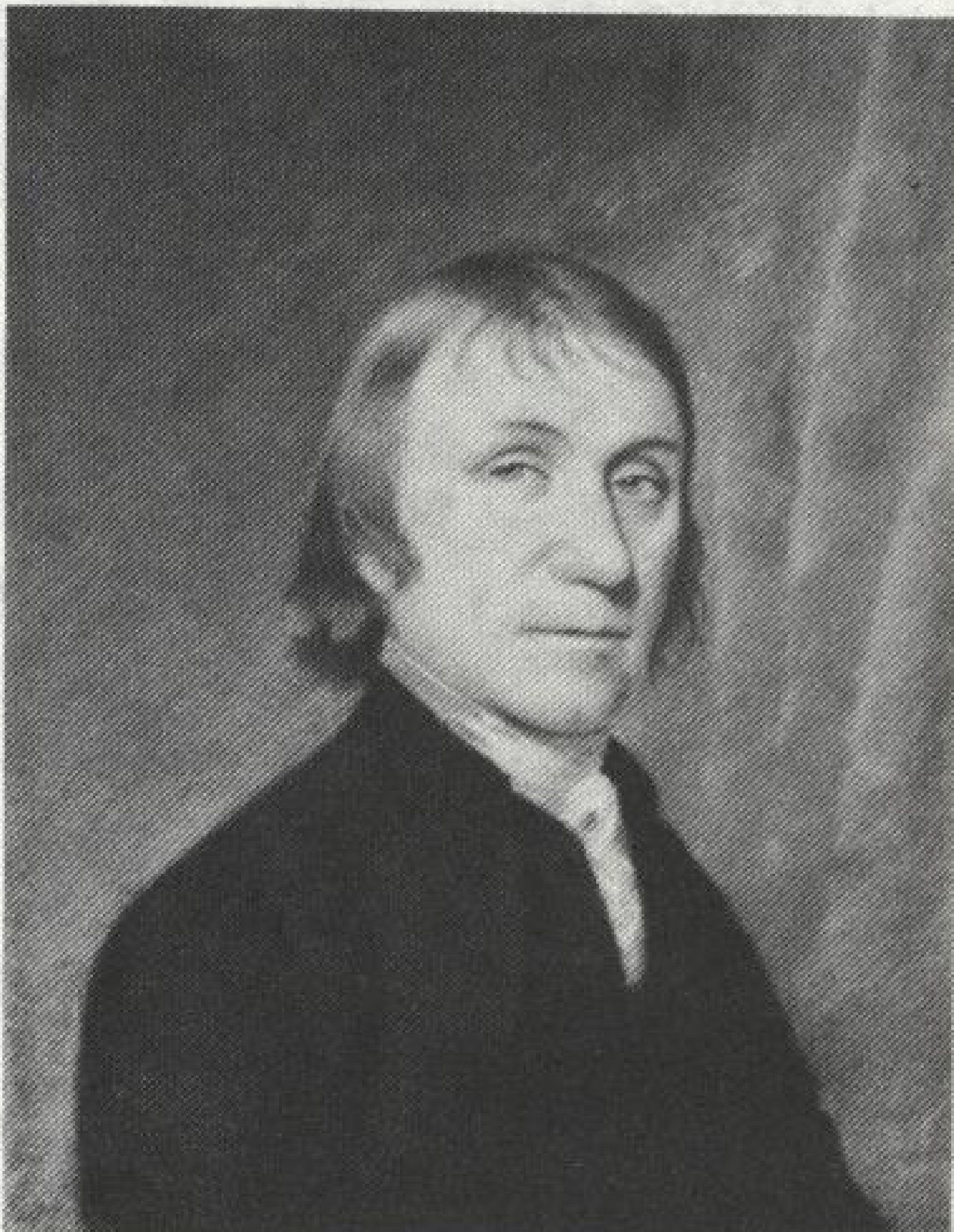


Fig. 34. Joseph Priestley, 1733–1804

(See p. 134)

chemistry at Glasgow in 1756, and ten years later followed his old master once more as professor of chemistry and physic in the University of Edinburgh, an appointment which he held from 1766 until his death in 1799.

Black qualified as a medical man, and his famous researches on 'fixed air' (carbon dioxide) arose out of his attempt to find a more suitable solvent for urinary calculi than the alkaline remedies then in use. In examining *magnesia alba* (basic magnesium carbonate) for this purpose, he found that it effervesced with acids, and changed by ignition (calcination, or heating in air) into a white powder devoid of this property, thereby losing seven-twelfths of its weight. Black showed that this loss of weight was due to a gas quitting the calcined material; this gas he characterised and called 'fixed air.' 'The volatile matter lost in the calcination of magnesia is mostly air,' he wrote, 'and hence the calcined magnesia does not emit air or make an effervescence when mixed with acids.'

This discovery, made in 1754, was of the first magnitude: for the first time, a gas had been weighed in combination. In a similar way Black showed that chalk (or marble), when calcined, underwent an analogous change: it lost weight, owing to the escape of the same invisible 'fixed air,' leaving a solid residue of quicklime. Black therefore viewed quicklime as chalk minus 'fixed air,' instead of regarding it in a phlogistic sense as chalk plus phlogiston. In 1757 he showed also that 'fixed air' is formed in the burning of charcoal.

Black individualised 'fixed air,' showing that it was a distinctive kind of 'air,' or gas, which could not be dismissed as a mere variety of atmospheric or common air. To this 'airy nothing' he gave, in the most literal sense, 'a local habitation and a name.' This epoch-making accomplishment, aided later by Priestley's new technique of pneumatic chemistry, opened the way to the isolation and recognition of other distinctive gases. The isolation and examination of these gases soon led in turn to the recognition of the compound nature of water, a discovery with which the name of James Watt, Black's most famous pupil, is inseparably linked.

Black's second series of researches dealt with his physical ideas of latent and specific heat, and were again of the first importance, for example in leading immediately to Watt's improvement of the steam engine. It was, however, the chemical discoveries of his first series of planned experiments, carried out in a logical sequence, that fired an astonishing train of further chemical investigations leading on through Scheele, Priestley, and Cavendish to Lavoisier and modern chemistry. Black's discovery that 'fixed air' could be held in a solid combination and weighed in that state contained not only the germ of Lavoisier's later theory of combustion; beyond this, Black's use of the balance in following chemical changes inaugurated another profound advance, this time in the development of quantitative chemistry.

The impact of this work upon contemporary scientific thought received an apt expression in 1803, after Black's death, from his colleague, John Robison, who pointed out that Black 'had discovered that a cubic inch of marble consisted of about half its weight of pure lime, and as much air as would fill a vessel holding six wine gallons. . . . What could be more singular than to find so subtile a substance as air existing in the form of a hard stone, and its presence accompanied by such a change in the properties of that stone? . . . What bounds could reasonably be set to the imagination, in supposing that other aereal fluids, as remarkable in their properties, might exist in a solid form in many other bodies?'

Black (Fig. **31**) established a great reputation as a teacher of chemistry during his long occupancy of the Edinburgh chair. He followed Cullen's practice of lecturing in English instead of in Latin. He aimed at making his teaching as plain and convincing as possible, since many of his students had 'a scanty stock of previous learning.'

Being an expert manipulator, he illustrated his lectures with effective experiments: 'the simplicity, neatness, and elegance with which they were prepared, were truly admirable,' wrote his biographer, Robison. His graphic exposition of a science now awakening from its long slumbers attracted many intelligent outsiders, so that, in this 'golden age of Edinburgh society,' in which Black figured so prominently, chemistry 'became a fashionable part of the accomplishment of a gentleman.'

Lord Brougham, who attended one of Black's last lecture courses, described in his memoirs how Black's experiments 'were often like Franklin's, performed with the simplest apparatus. . . . I remember his pouring fixed air from a vessel in which sulphuric acid had been poured upon chalk, and showing us how this air poured on a candle extinguished the light.' An extant manuscript version of these lectures, taken down by one of his audience, gives Black's verbatim description of some of these experiments, as, for example: 'Into this Glass Syphon, I shall pour a quantity of Lime Water. . . . I now apply my mouth to the pipe, and suck in the common air through it; The fluid bubbles a little, but is not altered in its transparency. . . . But I now blow through it, and it becomes instantly muddy, the fixed air from the Lungs being attracted by the Lime, it loses its solubility and is precipitated.'

Black's enterprise in teaching and his interest in the members of his class are shown by his foundation of a chemical society. Apparently the earliest of all chemical societies, in 1785 it numbered no fewer than fifty-nine members. The earliest chemical society in America—the Chemical Society of Philadelphia, founded by James Woodhouse in 1792—may also have owed its inception directly to Black, since Benjamin Rush, one of Black's earlier pupils, had been appointed in 1769 to the first American chair of chemistry, in the medical school of the University of Pennsylvania.

The early development of chemistry in America owed more to Scottish chemistry than to any other source. Indeed, the majority of American professors of chemistry, including incumbents of chairs at Pennsylvania, Harvard, Princeton, and Columbia, during the half-century after 1769 had studied chemistry in Scotland, where they imbibed the ideas of Cullen and Black. They were impressed by the value attached to lecture demonstrations, as well as, in a wider field, to the importance of applying chemistry in the arts and manufactures. Brougham records that Black 'never failed to remark on the great use of simple experiments within every one's reach; and liked to dwell on the manner in which discoveries are made, and the practical effect resulting from them in changing the condition of men and things.'

Black was a man of very delicate constitution. He had to avoid undue exertion and to diet himself carefully. Contemporary accounts describe his pleasant manner, his calm and unruffled air, his freedom from passion or prejudice, his readiness to enter into conversation, and his complete lack of affectation. He moved freely in society until his health began to fail. First and foremost a man of science, he was responsive to music and art, being 'a stranger to none of the elegant accomplishments of life . . . He performed on the flute, with great taste and feeling; and could sing a plain air at sight.' Although he remained a bachelor, he was a favourite with the ladies, who regarded themselves as honoured by his approbation and attention; 'for these,' wrote Robison, 'were not indiscriminately bestowed, but exclusively paid to those who evinced a superiority in mental accomplishments, or propriety of demeanour, and in grace and elegance of manners.'

Black brought the importance which he attached to the quantitative aspect to bear upon his private affairs. He took measured amounts of portions of his daily diet; and the bequests in his will were divided into 10,000 shares, distributed, as Robison observed, 'according to the degree in which each individual was the object of his care and solicitude.' Moreover, Black used the balance not only in weighing 'fixed air' in combination, but also in defeating the attempts of some of his students to 'multiply' gold at his expense, in the days when a professor's stipend was drawn largely from class-fees. 'I remember the first time I was ever in his society,' wrote Lord Brougham. 'When I went to take a ticket for his class, there stood upon his table a small brass instrument for weighing the guineas given. On learning who I was, he entered into conversation in a most kind manner. . . . When I was going away he said: "You must have been surprised at my using this instrument to weigh your guineas, but it was before I knew who you were. I am obliged to weigh them when strange students come, there being a very large number who bring light guineas; so that I should be defrauded of many pounds every year if I did not act in self-defence against that class of students." '

Black remained a somewhat lukewarm phlogistian for the greater part of his life, but unlike Priestley he sustained no brief for the theory; on the other hand, although eventually he accepted the new interpretation of combustion, his habitual restraint and reserve kept him from evincing any marked enthusiasm for Lavoisier's views. Pinning his faith upon experiment, he was a Laodicean in this controversy.

Very different from the career of Black was that of Carl Wilhelm Scheele (1742-86), who was born at Stralsund in Pomerania (then belonging to Sweden). One of a family of eleven children, he left school at the age of fourteen to become apprentice to an apothecary, and he remained in this calling for the rest of his life, working in succession at Malmö, Stockholm, and Uppsala, until he settled down at the small town of Köping in 1775. Scheele gained his chemical knowledge as he went along, partly from the works of Lemery, Boerhaave, and a few others at his command; but largely from his original experiments on the many substances which, as a pharmacist, he was called upon to handle.

Pre-eminently an experimentalist, Scheele became the greatest master of qualitative chemistry in the era between Boyle and Lavoisier. By so doing he met a crying need of the chemistry of his day for more information about elements, compounds, and chemical change. He employed the simplest kinds of apparatus; and since his work dealt mainly with the isolation of new substances and the examination of their properties, he was not concerned, like his contemporary, Black, with the use of the balance in following his observations.

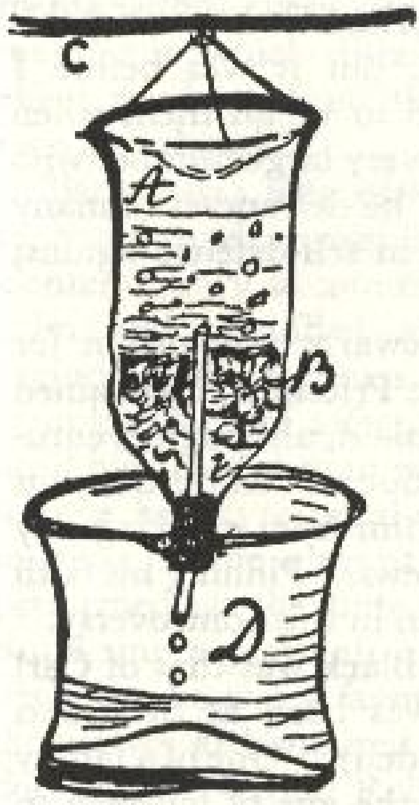


Fig. 32. Scheele's Apparatus for collecting Hydrogen

So early as 1770 Scheele had found how to produce 'inflammable air' (hydrogen) by treating iron or zinc with an organic acid and water, for which purpose he used the apparatus illustrated in Fig. 32: the hydrogen rises to the top of the inverted bottle, thereby expelling its own volume of liquid through the tube (D). Usually Scheele collected gases in a collapsed bladder fitted to the beak of the generating retort. Like Priestley, he regarded hydrogen as phlogiston, given up by the metal. However, here as so often Scheele pursued his experiments without much regard to the theory and clouded expression of contemporary writings: moreover, such writings were slow to reach him, since he mentioned in a letter of 1777 to Gahn, the Stockholm mineralogist, that he had not then seen Priestley's book of 1774.

Scheele was handicapped also through delay in the publication of his own discoveries. By 1773 he had isolated oxygen by heating silver carbonate, mercuric oxide, saltpetre, and other substances; but since this momentous discovery was not published until 1777 the priority is assigned, in conformity with the general practice, to Priestley (p. 134). Scheele showed that this new gas, which he called *Feuerluft* ('fire-air'), was identical with the 'lost air' which was absorbed from ordinary air by damp iron filings or by phosphorus; also that ordinary air consists of a mixture of about one part of 'fire-air' with four parts of 'spent air.'

Scheele's discoveries of important new substances can hardly have been equalled by any other investigator. In inorganic chemistry they included, among others, chlorine, hydrofluoric acid, silicon fluoride, arsine, arsenic acid, prussic acid, manganates and permanganates. There is an arsenic compound still known as 'Scheele's green,' and the mineral 'scheelite' is so named because Scheele examined it in 1781 and showed it to be calcium tungstate. Organic chemistry is equally indebted to Scheele, who was the discoverer of tartaric, citric, lactic, oxalic, and other organic acids, and also of glycerol, the so-called 'Scheele's sweet principle.'

Of Scheele (Fig. **33**) it has been said that 'brought up in a pharmacy, poor and modest, with no especial education, it is astounding that a man who only reached his forty-third year should have been able, during his short life, always tormented by material wants, to have arrived by means restricted and inconvenient at results which have had so mighty an influence on chemistry.'

His drive and enthusiasm in the midst of many cares and difficulties were unbounded. 'The elucidation of new phenomena is my sole concern,' he wrote in a letter to Gahn in 1774, 'and how happy is the investigator when the final success of his struggles brings joy to his heart!' Scheele was completely unself-seeking, as is clear from his reply to suggestions that he might leave Köping for a more attractive post: 'I cannot eat more than enough, and so long as I can obtain enough I need not seek my bread elsewhere.'

The unworldly attitude and unquenchable spirit of one who dedicated his life wholly to the service of science found lofty expression in another of his letters: 'You may think perhaps that material cares are going to absorb me, and take me away from experimental chemistry. Not so! That noble science is my ideal.'

The two great English contemporaries of Black and Scheele were Priestley and Cavendish. Joseph Priestley (1733-1804), a Yorkshireman born near Leeds, was a dogged and unrelenting phlogistian; and yet the famous experiment leading to his discovery of oxygen could not possibly have been inspired by Stahl's theory, according to which red calx of mercury [mercuric oxide] was merely the unprofitable residue left by the metal when it had been deprived of its phlogiston. Why, therefore, should this obdurate phlogistian have expected to obtain any useful result by heating such a dead mass? The answer to this question is probably twofold. First, Priestley (Fig. **34**) was a brilliant amateur of science, addicted, as he confessed, to making 'random experiments' in chemistry for the entertainment of his friends. Secondly, he had just obtained a new lens, or burning-glass, the most powerful heating-element of that day; and this new toy was of exceptional size, being twelve inches in diameter, with a focal length of twenty inches. And so, like an eager schoolboy, he 'proceeded with great alacrity to examine, by the help of it, what kind of air a great variety of substances, natural and factitious, would yield, putting them into . . . vessels . . . filled with quicksilver, and kept inverted in a bason of the same.'

The first day of August in the year 1774 is one of the most memorable dates in the history of science, and, indeed (although unknown to most historians), in the history of civilisation. On that sunny day, at Bowood near Calne in Wiltshire, where Priestley held the post of librarian and literary companion to Lord Shelburne, he focused his new glass upon some red calx of mercury, or *mercurius calcinatus* *per se*, obtained by heating the metal in air. In his own words, 'I presently found that by means of this lens, air was expelled from it very readily . . . what surprised me more than I can well express, was that a candle burned in this air with a remarkably brilliant flame . . . a piece of red-hot wood sparkled in it, exactly like paper dipped in a solution of nitre, and it consumed very fast.' Added to these marvels, a mouse 'remained perfectly at its ease' in the gas for twice the time it could have lived in an equal amount of air, and was 'quite lively and vigorous' when taken out.

The phlogistians naturally supposed that ordinary air already contained some phlogiston, because things were constantly burning in it. They thought that when a candle went out after burning in a confined parcel of air, the residual 'spent air' was completely saturated with phlogiston (which presumably occupied a negative volume!). Priestley concluded therefore that he had prepared an 'air' completely devoid of phlogiston, which could thus support combustion for a longer time than was possible with ordinary air, already contaminated with phlogiston. That was why he called the new gas 'dephlogisticated air.'

During a visit with Lord Shelburne to Paris in October 1774, Priestley met Lavoisier and told him about his recent discovery of the astonishing new 'air,' thus giving him a clue of great importance in the development of his views upon the nature of combustion. This visit led to a later controversy, concerning the discovery of oxygen.

Priestley had begun his study of 'different kinds of air' in 1767, when living in Leeds next door to a brewery to which he resorted as a source of 'fixed air' from the fermentation process. The experimental study of gases became a passion with him, and for their collection and examination he devised his celebrated 'pneumatic trough' (Fig. **35**), in which inverted water-filled glass cylinders for receiving the gas were supported on a perforated shelf submerged in water. His great contribution to 'pneumatic chemistry,' as the study of gases came to be called, included the discovery of a number of gases soluble in water, among them sulphur dioxide, ammonia, and hydrogen chloride; for Priestley collected his gases not only over water, as Boyle, Hales, and Mayow had done long before him, but in some instances over mercury.

Priestley seems to have looked upon his many new gases as ordinary air containing various amounts of phlogiston, that maid-of-all-work of contemporary theory. He took the study of some of these gases a long way. He showed that growing plants were able to 'restore' ordinary air which had been vitiated by combustion or by animals breathing in it (Fig. **35**); also that a mixture of common air and 'inflammable air' (hydrogen) when fired by an electric spark in a dry vessel, produced a dew on the inside of the glass, a pregnant observation which his obsession with phlogiston led him to dismiss casually with the remark that 'common air deposits its moisture by phlogistication.'

Priestley was a nonconformist minister, who devoted much of his energy and writings to religious controversy; and his consequent wide unpopularity was increased when he expressed open sympathy with the French Revolution. In 1791 a violent mob sacked his house and fired his chapel in Birmingham. So far back as 1767 he had attacked, with much reason and justification, the Governmental policy towards the American colonies; and in 1794 he sailed for America and settled at Northumberland, Pennsylvania, for the rest of his life. Priestley wrote voluminously on religious matters. His most celebrated scientific publication, *Experiments and Observations on Different Kinds of Air*, was published in six volumes between 1774 and 1786.

Priestley's great contribution to chemistry was made in the course of a stormy career which provided a notable contrast to the quiet and secluded life of his contemporary, the Honourable Henry Cavendish (1731-1810). Priestley, never possessed of much worldly wealth, was the son of a cloth-dresser; Cavendish was the millionaire grandson of a duke. Cavendish carried out systematic investigations rather than irregular experiments. Priestley's work was mostly qualitative; Cavendish was a brilliant exponent of quantitative work of great refinement and unprecedented accuracy. Thus, he differentiated between 'inflammable air' and 'fixed air' by making exact determinations of their specific gravities. Also, in 1781, in considering the curious contraction occurring in the 'phlogistication' of common air, he repeated Priestley's 'random experiment' made earlier that year: from this he concluded that 'when inflammable and common air are exploded in a proper proportion, almost all the inflammable air, and near one-fifth of the common air, lose their elasticity [disappear as gases], and are condensed into dew. And by this experiment it appears, that this dew is plain water, and consequently that almost all the inflammable air, and about one-fifth of the common air, are turned into pure water.'

Continuing this investigation, Cavendish found that the explosion of a mixture of two volumes of 'inflammable air' with one volume of 'dephlogisticated air' again led to the production of water, this time with almost complete disappearance of gaseous material. This crowning achievement of Cavendish showed that the supposed element, water, is composed of hydrogen and oxygen, a conclusion which was first put into specific words by James Watt, the pupil of Black. Cavendish's results, which remained unpublished until 1784, were meanwhile communicated to Lavoisier, leading thereby once more to a regrettable and unnecessary controversy about the priority of discovery.

In his orderly way, Cavendish now went still further with these explosion experiments. Confining ordinary air over a solution of caustic potash and sparking it repeatedly with additions of 'dephlogisticated air,' he showed that nitre (potassium nitrate) was produced, also that there remained a tiny gaseous residue amounting to 'not more than 1/120 part' of the ordinary air. This brilliant experiment had a twofold significance: first, it foreshadowed the discovery of argon by Raleigh and Ramsay in 1894; secondly, it pointed the way to the fixation of atmospheric nitrogen and the manufacture from the air of nitric acid and nitrates.

Meanwhile, in 1783, using Priestley's method of testing the 'goodness' of air by mixing it with nitric oxide, he found a contraction of 20·833 per cent., which is almost identical with the modern value for the percentage of oxygen in the atmosphere.

The stagnation of chemistry had gone. Only a few years before, in 1775, Priestley had written: 'There are, I believe, very few maxims in philosophy that have laid firmer hold upon the mind, than that . . . atmospherical air . . . is *a simple elementary substance*, indestructible, and unalterable, at least as much so as water is supposed to be.'

Cavendish possessed a withdrawn and aloof personality, so markedly eccentric that perhaps, in view of his great reputation, it was largely responsible for the legend that the man of science is of necessity a somewhat inhuman creature with few interests beyond his own specialised work. Certainly, with Cavendish, science seemed to be the grand passion of an otherwise colourless life. He was so shy and abstracted that only one portrait of him is known, and that had to be made surreptitiously. It bears out the statement that he wore antiquated clothing and hung the same old shovel-hat on the same peg for forty years and more. His great wealth gave rise to annoyance with his bankers; and he is said to have had 'a peevish impatience of the inconveniences of eminence,' combined with a disinclination to conversation, and a dislike of all towns except London, of all meats except mutton, and of all women with no exception.

According to a biographer, Cavendish regarded the universe as consisting 'solely of a multitude of objects which could be weighed, numbered, and measured; and the vocation to which he considered himself called was, to weigh, number, and measure as many of these objects as his alloted three-score years and ten would permit. He weighed the Earth; he analysed the Air; he discovered the compound nature of Water; he noted with numerical precision the obscure actions of the ancient element, Fire.'

Cavendish will remain as one of the outstanding figures of science. He was at the same time chemist, physicist, mathematician, and astronomer; besides being, in the witty words of the French physicist, Biot, 'le plus riche de tous les savans, et probablement aussi le plus savant de tous les riches.'

The End—and the Beginning

Phlogiston was now tottering to its fall. Destiny beckoned to the illustrious Frenchman, Antoine Laurent Lavoisier (1743-94) to administer the *coup de grâce.* At the age of twenty-one he had qualified for the law; but meanwhile Rouelle's lectures on chemistry at the Jardin du Roi in Paris (p. 105) had awakened in him a vivid interest in this science. Lavoisier soon began to undertake chemical researches himself, and in a few years he had acquired such a reputation as a scientist that he was elected to the Académie des Sciences. Unlike Cavendish, however, Lavoisier did not combine the study of the Hermetic Art with the life of a hermit. Suave, polished, and eloquent, he was a man of the world who mingled freely in society and took part in public affairs. So it came about that quite early in his career he became a *fermier général*, responsible under the established system for the collection of taxes. Moreover, he applied his scientific knowledge and administrative ability to the fostering of agriculture and in many other national matters. Such a man, masterful, full of ardour, and fired by ambition, was bound to make a mark in the history of his time.

In 1771 he married his charming and accomplished ward, who helped him in his laboratory and made French translations of the writings of Priestley and Cavendish. After his death she married the American physicist, Count Rumford.

In science, Lavoisier brought his keen intelligence to bear, from 1770 onwards, upon the intriguing riddle of the nature of combustion. In his investigations, isolated facts did not interest him; he left nothing to speculation when experiment could decide it; and he paid constant attention to the quantitative aspect of his carefully chosen experiments. He made a close study of the burning of phosphorus and the calcination of tin and lead. Boyle, a century before him, had heated a weighed amount of tin in a sealed retort containing air, and upon breaking the seal had recorded: 'whereupon I heard the external air rush in . . . because the air within was highly rarefied.' Lavoisier, repeating this experiment and using the balance at every stage, brushed aside Boyle's ascription of the increase of weight to the absorption of igneous particles, and came to the correct conclusion that air consists of at least two gases, one of which disappears during the calcination. Here, of course, he was helped by Black's proof that a gas could enter into a solid combination and be weighed in that state.

In the same year, 1774, there happened the historic meeting in Paris between Lavoisier and Priestley (p. 135). Lavoisier's quick mind leapt inevitably to the conclusion that the absorbed part of the air was the same as the 'dephlogisticated air' of Priestley, which supported combustion with such vigour. He confirmed this conclusion by the famous 'Lavoisier's experiment,' which proved that the air absorbed by heating mercury in a closed vessel (shown diagrammatically in Fig. 36) was equal in volume to the 'dephlogisticated air' liberated by heating more strongly (Fig. 37) the red calx of mercury from the first experiment. This simple and conclusive practical demonstration dealt the final blow—the *coup de grâce*—to the theory of phlogiston. In general, Lavoisier's numerous experiments on the calcination or combustion of a variety of metals (including tin and lead) and non-metals (including carbon, sulphur, and phosphorus) led him to the irrefutable conclusion that the supposed loss of phlogiston in all such processes was in reality combination with an active gaseous constituent of the atmosphere, to which he gave the name oxygen; 'spent air' (p. 133) became azote, or nitrogen.

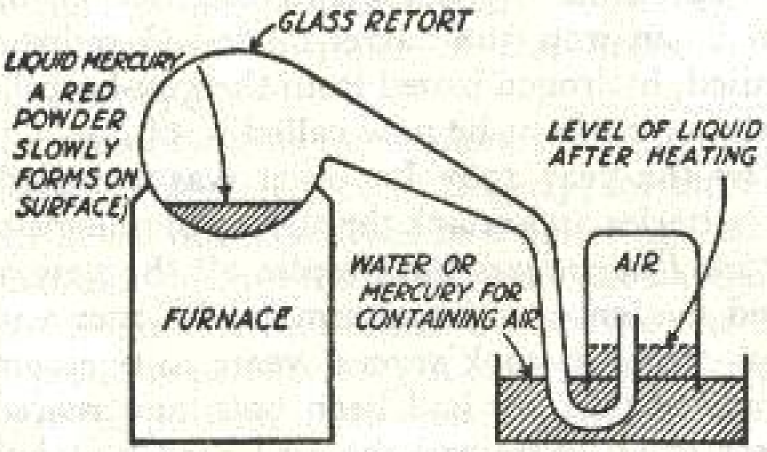


Fig. 36. Lavoisier's Experiment: mercury heated in air absorbs oxygen

His establishment of 'fixed air' as an oxide of carbon in 1783 extended in still another direction the ramifications of Black's key research; for carbon dioxide, together with water, is an invariable product of the combustion of organic matter; and Black himself had shown in 1757 that 'fixed air' is formed in the burning of charcoal.

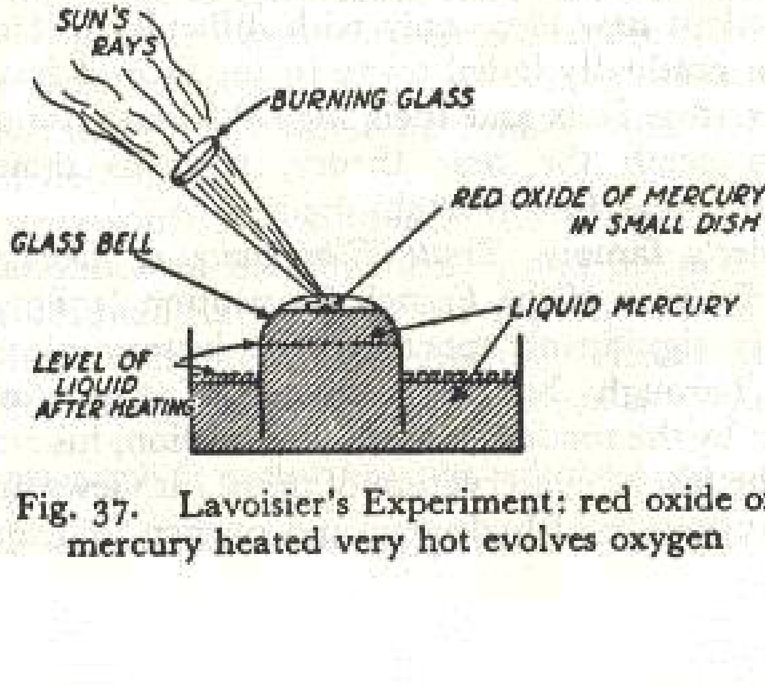


Fig. 37. Lavoisier's Experiment: red oxide of mercury heated very hot evolves oxygen

Turning to the related problem of the constitution of water, Lavoisier first of all confirmed Cavendish's synthetic experiments in which water was formed from its two constituent elements, hydrogen and oxygen. Next, he devised an analytical proof by passing steam over iron filings contained in an iron gun-barrel heated to redness: as he had surmised, hydrogen issued from the gun-barrel, leaving a solid calx, or oxide as he now called it, of iron.

Thus, by the year 1783 Lavoisier was impelled to unmask his batteries and attack the theory of phlogiston in his *Réflexions sur Phlogistique*; but despite all the new and well marshalled evidence at his command he met with great opposition, which it took several years to overcome. All the chemists of that era had been born and reared in the atmosphere of an ingrained theory which had held sway for several generations. A formidable mental obstacle barred the progress of the new theory; for the law of inertia applies to the human mind as well as to inanimate bodies. Perhaps the most difficult of all mental activities lies in the ability to realign a series of familiar facts and relationships and to give them a completely new interpretation. Lavoisier himself realised this: 'I do not expect,' he wrote, 'that my ideas will be adopted all at once; the human mind adjusts itself to a certain point of view, and those who have regarded nature from one angle, during a portion of their life, can adopt new ideas only with difficulty.' However, opposition gradually faded away in the face of Lavoisier's incontrovertible facts and their logical interpretation, and before his death the new theory, with its momentous implications, was firmly established.

'Lavoisier's famous *Traité Elémentaire de Chimie*, published in the year of the French Revolution (1789), marks an equally significant epoch in the history of physical science. Through his replacement of the theory of phlogiston by the modern view of combustion, his establishment of the law of conservation of mass, his views upon the elementary nature of hydrogen and oxygen and upon the constitution of alkalies and salts, his introduction of a rational system of nomenclature, and his insistence upon the quantitative aspect, Lavoisier exalted chemistry for all time to the rank of an exact science. Furthermore, by his work on the composition of organic substances, he laid one of the foundation-stones of the branch-science of organic chemistry.'[1]

Thus Lavoisier became the founder of the modern science of chemistry. His life ended in tragedy; for although as a chemist he could not have lived in a better age, as a public figure in revolutionary France he could not have lived in a worse. As a chemist he reaped the reward; as a man of affairs he paid the penalty.[2] His execution, in 1794, in the plenitude of his powers, on the trivial charge of abusing his office of *fermier général* by 'adding to tobacco, water and other ingredients detrimental to the health of the citizens,' was the most insensate of the unnumbered crimes of the French Revolution. In him the revolutionaries sacrificed one of the very greatest men their country has ever produced.

In chemistry, Lavoisier shed a dazzling new light upon the long labours of generations of devoted workers, and opened out a new world to his successors. In the words of Liebig: 'He discovered no new body, no new property, no natural phenomenon previously unknown; all the facts he established were the necessary consequences of the labours of those who preceded him. His merit, his immortal glory, consists in this—that he infused into the body of science a new spirit.'

That new spirit still animates the progress of science; for the abolition of the old theories and the accumulation of accurate quantitative data led rapidly to the formulation of that comprehensive Atomic Theory whose innumerable ramifications form the nervous system of the

[1] This paragraph is quoted from the writer's *Text-book of Organic Chemistry*.

[2] *Humour and Humanism in Chemistry*, p. 152.

wonderful body of physical science as we know it today.[1]

Alchemy, in Basilian phrase (p. 56), had been burned entirely to ashes in a great fire; but by this process Chemistry had been liberated. 'Alchemy,' wrote Francis Bacon in the days of its power, 'may be compared to the man who told his sons that he had left them gold buried somewhere in his vineyard; where they by digging found no gold, but by turning up the mould about the roots of the vines, procured a plentiful vintage. So the search and endeavours to make gold have brought many useful inventions and instructive experiments to light.'

More than two centuries later, when Alchemy had blossomed into modern Chemistry, Liebig exclaimed: 'Is that Science not the Philosopher's Stone which changes the ingredients of the crust of the earth into useful products, to be transformed, by commerce, into gold? Is that knowledge not the Philosopher's Stone which promises to disclose to us the laws of life, and which must finally yield to us the means of curing disease and of prolonging life?' The old ideals of alchemy in search of gold, and alchemy in the service of medicine, have given way in this modern age to the wider vision of chemistry in the service of man.

[1] *Text-book of Organic Chemistry.*

IX · THE DEVELOPMENT OF MODERN CHEMISTRY

Interregnum

THE great edifice of modern chemistry has arisen upon the twin foundation-stones of Lavoisier's Oxygen Theory of Combustion and Dalton's Atomic Theory of the constitution of matter. It is often overlooked that a period of some twenty years separated these two conceptions. It is true that with the acceptance of Lavoisier's views it could have been said that 'now sits expectation in the air'; but meanwhile the dormant science, awakening slowly from its age-long sleep, passed through a confused interregnum, coincident in world history with the rise to power of Napoleon Bonaparte and the consolidation of the former American colonies into a rapidly growing democratic republic.

The state of chemistry in this period finds an interesting reflection in the printed version of Black's *Lectures on the Elements of Chemistry,* issued in 1803 as a posthumous work edited by Robison. A primary difficulty lay in the classification of substances. As Black could not 'determine what are the ultimate elements of bodies,' he arranged them in the arbitrary classes of Salts, Earths, Inflammable Substances, Metals, and Waters. His fifteen metals were, in order: arsenic, magnesium [manganese], iron, mercury, antimony, zinc or spelter, bismuth or tin-glass, cobalt, nickel, lead, tin, copper, silver, gold, and platina or platinum. The curiosities of this classification are well brought out in the grouping of 'nitrous air' (nitric oxide) and 'various oxyds of azote' (oxides of nitrogen) with mercury; and of 'dephlogisticated muriatic acid' (chlorine) with manganese. In spite of the cumbrous character of phlogistic names, Black did not relish the new system of chemical nomenclature formulated in 1787 at Paris by 'Messrs. Lavoisier, De Morveau, Berthollet, and Fourcroy.' Their 'latinised French words' seemed to him 'very harsh and disagreeable,' as well as being so framed as to make it 'scarcely possible to think on chemical subjects in a way different from their theories.'

The motive power of the coming advance lay in the rapid accumulation of quantitative data dealing with chemical change. In 1766 Cavendish determined the relative weights of potash and lime required to neutralise identical weights of an acid, and he called these relative weights 'equivalent weights' of potash and lime. Later, it was found that certain pairs of salts, when mixed in the right proportions, could undergo a process now known as 'double decomposition,' thereby forming new pairs. This first apprehension of the idea of equivalent weights of substances was elaborated by Richter, who in 1794 gave exact proportions by weight for the neutralisation of a series of acids by another series of bases.

More significant still, in 1799 Proust had put forward the Law of Fixed Proportions, according to which: When combination between elements takes place, it is in definite proportions by weight, so that the composition of a pure chemical compound is independent of the way in which it is prepared. This law, also known as the Law of Constant Composition, may be restated in the words: The same compound always contains the same elements combined together in the same proportions by weight.

Some years earlier, Lavoisier's quantitative work had set the seal upon the Law of the Conservation of Matter, according to which matter can neither be created nor destroyed in chemical reactions. In his *Traité* (1789), Lavoisier stated: 'on peut poser en principe que, dans toute opération, il y a une égale quantité de matière avant et après l'opération, que la qualité et la quantité des principes est la même, et qu'il n'y a que des changements, des modifications. C'est sur ce principe qu'est fondé tout l'art de faire des expériences en chimie.'

Besides all this, the activities of chemists during the interregnum had led to the discovery of a large number of new compounds and of some new elements, including notably the spectacular isolation by Humphry Davy of the metals potassium and sodium in 1807, on the very eve of the annunciation of Dalton's Atomic Theory.

The Atomic Theory

It has already been mentioned that an atomistic view of the constitution of matter was put forward by certain philosophers in ancient Greece (p. 5). They had done this in a purely speculative way; moreover, even their speculations were heavily discounted by the weighty influence of Aristotle's opposed view of the continuity of matter. The Atomic Theory of John Dalton (1776-1844) owed nothing to any of the thinkers of ancient Greece; to what has been termed 'the airy hypothesis of a philosopher who soars above the vulgar paths of observation and experience.' In the seventeenth century, both Gassendi and Boyle had held atomistic views; and, far more important, Newton, with his unprecedented mathematical and physical knowledge, also held the opinion that matter possessed an atomic constitution.

According to Newton's view, as expressed in his *Opticks* (1704): 'It seems probable to me, that God in the beginning formed matter in solid, massy, hard, impenetrable, movable particles; of such sizes and figures, and with such other properties, and in such proportion to space, as most conduced for the end for which He formed them; and that these primitive particles being solids, are incomparably harder than any Porous bodies compounded of them; even so very hard, as never to wear or break in pieces: no ordinary power being able to divide what God Himself made One, in the first creation. . . . God is able to create particles of matter of several sizes and figures, and in several proportions to the space they occupy, and perhaps of different densities and forces.' The law of the conservation of matter is implicit in this statement.

Newton was influenced by the work of his contemporary Boyle, on the compressibility of air (1660-62), leading to the discovery of Boyle's Law (p. 112). In his *Principia* (1687), Newton gave a mathematical treatment of the condition under pressure of an elastic fluid (gas), supposing it to consist of particles (now known as molecules): 'If the density of a fluid gas which is made up of mutually repulsive particles is proportional to the pressure, the forces between the particles are reciprocally proportional to the distances between their centres. And *vice versâ*, mutually repulsive particles, the forces between which are reciprocally proportional to the distances between their centres, will make up an elastic fluid, the density of which is proportional to the pressure.'

Thus, the atomistic ideas had filtered down through the ages to Dalton, who was an heir of all these ages; but never yet had any exponent of these ideas been in a position to attempt to assign precise relative sizes or weights to the hypothetical atoms. It was during a prolonged series of meteorological observations and researches on gases that Dalton, to quote his own words, was led to 'speculate upon the nature and constitution of the atmosphere. . . . Newton had demonstrated clearly . . . that an elastic fluid is constituted of small particles or atoms of matter which repel each other by a force increasing in proportion as their distance diminishes. . . . It occurred to me that I had never contemplated the effect of the *difference of size* in the particles of elastic fluids. . . . The different *sizes* of the particles of elastic fluids under like circumstances of temperature and pressure being once established, it became an object to determine the relative *sizes* and *weights*, together with the relative *numbers* of atoms in a given volume. This led the way to the combination of gases and to the number of atoms entering into such combinations.'

As in the solution of the problem of combustion, it was the study of gases that opened the way once again to a decisive advance. The twin foundation stones of Lavoisier's Oxygen Theory and Dalton's Atomic Theory, upon which modern chemistry rests, were both laid as a result of the study of gases.

In 1801 Dalton applied Newton's atomic conception in accounting for his own observation that a mixture of confined gases exerts a pressure equal to the sum of the partial pressures, that is, each gas exerts its own pressure, independently of its companion gases. A little later, in 1803, he followed up this discovery of the Law of Partial Pressures by announcing that the amount of any one gas dissolved in water from a mixture of gases is proportional to its partial pressure. These investigations show how Dalton's mind was working in shaping the Atomic Theory. It was in 1804, at Manchester, that Dalton first broached his theory to Dr. Thomas Thomson, who immediately saw its enormous importance and gave the first printed account of it in the third edition of his *System of Chemistry*, in 1807.

Dalton's ideas acquired still more precision from his experiments on the composition of 'olefiant gas' (ethylene) and 'carburetted hydrogen' (methane). Each of these gases contains carbon and hydrogen only, and Dalton found the latter to have exactly twice as much hydrogen, in relation to carbon, as the former. According to his budding theory, he conceived the ultimate chemical particle of olefiant gas to contain one atom of carbon and one of hydrogen, and that of carburetted hydrogen to contain one atom of carbon and two atoms of hydrogen. He then applied the same procedure to 'carbonic oxide' (carbon monoxide), ammonia, water, and other simple substances. By the year 1808, his ideas had become sufficiently settled to find publication in the first part of his historic *New System of Chemical Philosophy*, the second and third volumes of which appeared in 1810 and 1827, respectively.

The 'Golden Tripod,' as Count Michael Maier might have called it, upon which the Atomic Theory was originally based consisted of three laws which summarised the results of numerous quantitative experiments on a large variety of substances. The Law of Fixed Proportions states that elements combine together in fixed proportions by weight. According to the Law of Multiple Proportions, when two or more compounds are formed from the same two elements, the different weights of one which combine with a constant weight of the other bear a simple ratio to each other. The Law of Reciprocal Proportions states that the proportions in which two elements combine separately with a third element are in a simple ratio to those in any compound of the first two elements.

The first of these laws was established by Proust in 1799. Dalton himself proved the law of multiple proportions by his researches on olefiant gas and carburetted hydrogen, and on other substances. The third law first became apparent from the neglected work of Richter on the quantitative neutralisation of acids by bases (p. 146). Soon after the publication of the Atomic Theory, the great Swedish chemist, Berzelius, wrote to Dalton saying that 'the theory of multiple proportions is a mystery without the atomic hypothesis.'

According to Dalton's 'Atomic Theory,' the 'simple atoms' of a particular element are perfectly alike in weight and figure; they can neither be created nor destroyed; and they may unite in simple proportions with other 'simple atoms' to form 'compound atoms' [later called molecules], consisting of small whole numbers of the elements concerned.

In drawing up his rudimentary list of atomic weights, Dalton adopted the atomic weight of the lightest element, hydrogen, as unity, and referred the relative weights of other kinds of atoms to this standard. This was all that he could do, since he realised the impossibility at that time of determining the absolute weight (or mass) of the hydrogen atom (which much later was found to be $1{\cdot}66 \times 10^{-24}$

gram). In determining relative atomic weights Dalton relied solely on the results of quantitative analysis. Here it must be realised that the percentage composition of a substance in quantity is identical with that of each of its ultimate chemical particles (molecules), since these, *ex hypothesi*, are all alike.

To take one of Dalton's examples, water was found by analysis to contain 8 parts by weight of oxygen combined with 1 part of hydrogen. At this point there came a stumbling block, because Dalton had no means of finding out the number of 'simple atoms' of hydrogen in a 'compound atom' of water. This obstacle, insuperable at the time, led to much confusion during the next half century. All that Dalton could do was to assume the simplest possibility of the presence of only one 'simple atom' of each element in the 'compound atom' of water. Then, if the 8 parts of oxygen and the 1 part of hydrogen each represented one atom, it followed that the oxygen atom would be 8 times as heavy as the hydrogen atom, i.e. its relative weight would be 8; and that was Dalton's value for the atomic weight of oxygen. Eventually, however, it was found that the ultimate chemical particle (molecule) of water contains 2 hydrogen atoms united with 1 oxygen atom: thus 1 atom of oxygen is 8 times as heavy as 2 atoms of hydrogen, and 16 times as heavy as 1 atom of hydrogen. The atomic weight of oxygen is therefore 16, and not 8, as Dalton supposed. Errors of this kind ran unavoidably through the early determinations of atomic weights by Dalton and others: as another example, the atomic weight of the important element, carbon, was supposed to be 6, instead of 12.

Curiously enough, a method of solving this problem had already been provided by the Italian physicist, Avogadro, in 1811, who from a study of the general physical properties of gases, notably their universal obedience to Boyle's Law, came to the conclusion that equal volumes of all gases at the same temperature and pressure contain equal numbers of molecules. That is another way of saying that gases are ideal democratic communities, in which every molecule (which is pictured in rapid and incessant motion) has the same 'living space.' Thus, by comparing the weights of equal volumes of two gases under similar conditions, one is comparing the weight of one molecule of the first gas with one molecule of the second. If the first gas is hydrogen, the value obtained for the second is called its gaseous density. Knowing, from other evidence, that the hydrogen molecule contains two atoms of hydrogen linked together in combination, it follows that the molecular weight of a gas (or vaporised substance)—that is to say, the weight of its molecule compared with the weight of one hydrogen atom—is twice its gaseous density.

The enormous significance of 'Avogadro's Hypothesis' remained unappreciated until 1858, two years after his death, when his fellow-countryman, Cannizzaro, pointed out how it could be used in finding the true values of atomic and molecular weights. Avogadro had been inspired by a slightly earlier discovery of the French chemist, Gay-Lussac, who enunciated in 1808 the Law of Gaseous Volumes, which states that when chemical changes occur between gases their volumes are simply related to one another and to the volumes of the products, if these are gaseous. The earliest example of this law may be seen in Cavendish's observation (p. 137) that 2 volumes of hydrogen combine with 1 of oxygen to yield water.

Dalton was obsessed by his dictum of atomic integrity, an example of his *a priori* attitude of mind which he once expressed to his friend, Dr. Ransome, in the naïve words, 'Thou knows it must be so, for no man can split an atom.' Consequently he failed to realise that the ultimate chemical particle (molecule) of an element could contain more than one atom of the element: hence he was unable to reconcile his views with Gay-Lussac's results. Soon after Dalton's publication of the Atomic Theory, Berzelius thought fit to reprove him mildly for casting doubt upon the accuracy of Gay-Lussac's work. 'I should have thought rather,' he wrote to Dalton, 'that these experiments were the finest proofs of the probability of the atomic theory; and I confess to you, that I do not easily think Gay-Lussac is in fault, especially in a matter when the point is measuring [i.e. experimental accuracy].'

Dalton, in line with alchemical practice, represented elements and compounds by symbols—with one important difference. An alchemical symbol represented the substance in mass, or indefinite quantity; whereas Daltonian symbols represented one 'simple atom' or one 'compound atom' of the substance. Some of these symbols are shown in Fig. 38.

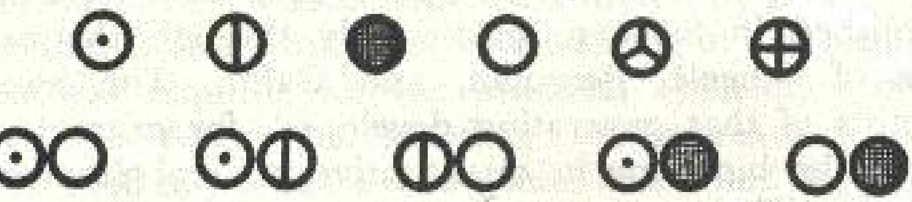


Fig. 38. Some Daltonian Symbols

Later, Berzelius replaced the Daltonian symbols by letters, and here again the letter represented one atom of the element concerned. The modern notation of the symbols shown in Fig. 38 are H, N, C, O, P, S, for the elements; and HO, HN, NO, HC, OC for the compounds. Each of the latter group would now be called a molecular formula, which shows the kind and number of each atom in the molecule which it represents. The corrected molecular formulae for those shown in Fig. 38 are, in fact: H_2O (water), NH_3 (ammonia), NO (nitric oxide) C_2H_4 (ethylene), and CO (carbon monoxide).

Dalton (Fig. **39**) was an accurate gas analyst, although not possessed of Cavendish's proficiency as a quantitative experimentalist of the first rank. Indeed, Sir Humphry Davy said of Dalton that 'he was a very coarse experimenter, and almost always found the results he required, trusting to his head rather than to his hands.' It has been pointed out, however, that the aim of Dalton's practical work was 'to assemble rapidly a multitude of examples, especially of the significant class of multiple proportions. Precise numerical exactitude, however abstractedly desirable, was not an essential requirement. . . . Dalton valued detailed facts mainly, if not solely, as the stepping-stones to comprehensive generalisations.'

Once established, the Atomic Theory certainly called for a multitude of exact quantitative determinations, in particular of atomic weights of all the known elements. It was in this field that the illustrious Swedish chemist, Jöns Jacob Berzelius (1779-1848), made a contribution of the first magnitude and importance to the growing science of chemistry. A tradition of analytical skill had been established in Sweden, particularly through the earlier work of Scheele, Bergman, and Gahn. The Swedish chemists of that generation developed, for example, the use of the blowpipe in quantitative mineral (inorganic) analysis. Their great successor, Berzelius, displayed a hitherto unexampled skill in quantitative chemical analysis. Inspired by the work of Richter upon metallic salts in solution (p. 146), he began precise quantitative work upon such substances in 1807, and was quick to see the significance of his work in the light of Dalton's law of multiple proportions and Atomic Theory. Henceforward he devoted his energies and unsurpassed manipulative skill to assembling proofs of the new theory, originally in inorganic chemistry and later in the newer province of organic chemistry.

Berzelius' reputation was such that he became recognised as the 'chemical law-giver' of his age. He was ennobled by Charles XIV, and to the modest little laboratory adjoining the kitchen in his home at Stockholm came many ambitious young chemists, most of whom later achieved fame. Among them was Friedrich Woehler, a young man of twenty-three who arrived at Berzelius' house early one morning in October 1823. 'My heart beating rapidly,' wrote Woehler long afterwards, 'I stood before Berzelius' door and rang the bell. The door was opened by a man of distinguished appearance, neatly clad and in the prime of life. It was Berzelius himself [Fig. 40]. . . . I followed him into his laboratory like one in a dream, doubting whether I could really be in this classical place which was the goal of my desires.' Berzelius set Woehler to work upon a series of mineral analyses. Some of his results were discordant. 'Doktor!' exclaimed the vigilant Berzelius, who spoke German, French, and English, besides his native Swedish, 'Das war geschwind, aber schlecht! (Doctor, that was fast but faulty!).'

Such was the man who set the Atomic Theory upon a firm and enduring basis. In his famous *Lehrbuch der Chemie* he wrote: 'I soon convinced myself by new experiments that Dalton's numbers were wanting in that accuracy which was requisite for the practical application of his theory. . . . After work extending over ten years . . . I was able in 1818 to publish a table which contained the atomic weights, as calculated from my experiments, of about 2,000 simple and compound substances.'

Something must now be said about John Dalton himself. He was born in 1766 at the tiny village of Eaglesfield, in Cumberland, being one of six children, of whom three died early. His parents Joseph and Deborah Dalton, were Quakers. His father was a 'respectable yeoman' who was also a weaver, and John took part as a boy in the work of the small farm. He summarised the earlier course of his career in the following terse and typical manner: 'Attended the village schools, there [Eaglesfield] and in the neighbourhood, till eleven years of age, at which period he had gone through a course of mensuration, surveying, navigation, &c.; began about twelve to teach the village school, and continued it two years; afterwards was occasionally employed in husbandry for a year or more; removed to Kendal at fifteen years of age as assistant in a boarding-school; remained in that capacity for three or four years, then undertook the same school as principal, and continued it for eight years; whilst at Kendal, employed his leisure in studying Latin, Greek, French, and the mathematics, with natural philosophy; removed thence to Manchester in 1793 as tutor in mathematics and natural philosophy in the New College; was six years in that engagement, and after was employed as private and public teacher of mathematics and chemistry in Manchester, but occasionally by invitation in London, Edinburgh, Glasgow, Birmingham, and Leeds.'

Dalton was mainly self-taught, and his upbringing was such as to render him frugal, self-reliant and persevering and to endow him with a 'severe, patient concentration of thought.' It has been said that as a consequence of his education he was 'deficient in the art of chemistry' and that he pursued science always with mathematical views. His reliance upon his own ideas is reflected in his statement that although he could carry his library on his back he had not read half of it. According to Dr. John Davy, he was devoid of grace, with a stiff and awkward manner and a dry style of writing and conversation. 'Independence and simplicity of manner and originality were his best qualities,' added Davy, and although 'in comparatively humble circumstances he maintained the dignity of the philosophical character.' Throughout his life he retained a command of the broad Cumbrian dialect which he spoke as a boy.

Although, like Joseph Black, he remained a bachelor, it is said of him that, again like Black, and 'like most men of higher sensibility and intelligence, [he] greatly enjoyed the society of women of superior talents and mental culture.' Writing to his brother Jonathan in 1796, he made a warmly appreciative reference to two sisters of his acquaintance: 'I never met with a character so finished as Hannah's. . . . She is well pleased with the conversation of literary and scientific people, and has herself produced some essays that would do credit to the first geniuses of the age, though they are scarcely known out of the family, so little is her vanity. . . . Next to Hannah, her sister Ann takes it in my eye before all others. She is a perfect model of personal beauty . . . but in strength of mind and vigour of understanding must yield to her elder sister.' He continued, 'I dwell with pleasure upon the character of these two amiable creatures,' adding with characteristic caution, 'but would not have thee communicate my sentiments to others.'

Besides preserving the Quaker habit of speech, with its usage of the second personal pronoun, he affected the sober Quaker garb, with its drab coat and waistcoat, white neckcloth, knee-breeches, grey hose, and buckled shoon. On the occasion of his presentation to King William IV he declined, as a Quaker, to wear the sword forming part of the Court dress; but fortunately he was able to conceal the deficiency with the aid of his ample D.C.L. gown.

This founder of the great theory which since its inception has dominated every advance in physical science, disclaimed all pretension to genius, of which, indeed, he denied the existence. He once said that the germ of the idea came into his youthful mind before he had acquired any special knowledge of chemistry, a statement which bears out an opinion that he reasoned deductively from the theory to facts, rather than inductively from facts to the theory. In his own eyes, his achievement came solely as the result of 'persevering industry devoted to a single practicable object.' Self-reliance, concentration, singleness of purpose: such was the endowment enabling this humble farm-lad to justify those words which Tomais Norton of Briseto wrote in 1477: 'Almighty God from great Doctours hath this *Science* forbod, and graunted it to few Men of his mercy, such as be faithful trew and lowly.'

Some First-fruits of the Atomic Theory

Chemistry advanced with an increasing momentum as a result of the painstaking experimental work of Berzelius and many other chemists of his time, particularly after the clarification of the character of atoms and molecules which had followed quickly upon the application of Avogadro's

Hypothesis in 1858. All kinds of matter, whether gaseous, liquid, or solid, came to be regarded as consisting of excessively minute ultimate particles, called molecules. Some of the consequent ideas may now be outlined. The molecules of any specific substance resemble each other precisely. All molecules are constructed of atoms. Those of elements contain atoms of one kind only; those of compounds contain two or more kinds of atoms. The molecular formula shows the kinds of atoms in the molecule and the number of each kind. Thus, the element hydrogen has the molecular formula H_2, which shows that its molecule consists of two hydrogen atoms joined together, linked, or combined. Similarly, the element oxygen has the molecular formula, O_2. Simple molecular formulae of compounds may be illustrated by H_2O (water), NH_3 (ammonia), and H_2SO_4 (sulphuric acid). Any change which does not affect the composition of the molecule is called a physical change and leaves the substance unaltered chemically. A chemical change alters the molecular composition and leads to a new substance, or substances.

The concise symbolic notation of modern chemistry, although much less picturesque than alchemical symbolism, enables chemical changes to be represented very simply and fully, particularly by means of chemical equations. These equations embody the leading principle that the chemist must cultivate two-dimensional thought: he must learn to interpret chemical symbolism both qualitatively and quantitatively. For example, the complete expression of Cavendish's explosion of a mixture of hydrogen and oxygen is given by the equation:

$$2H_2 + O_2 = 2H_2O.$$

Qualitatively, this equation means that hydrogen and oxygen combine to form water and nothing else, under the conditions of the experiment. Quantitatively, it may be interpreted in several ways. First, it shows that 2 molecules of hydrogen combine with 1 molecule of oxygen to give 2

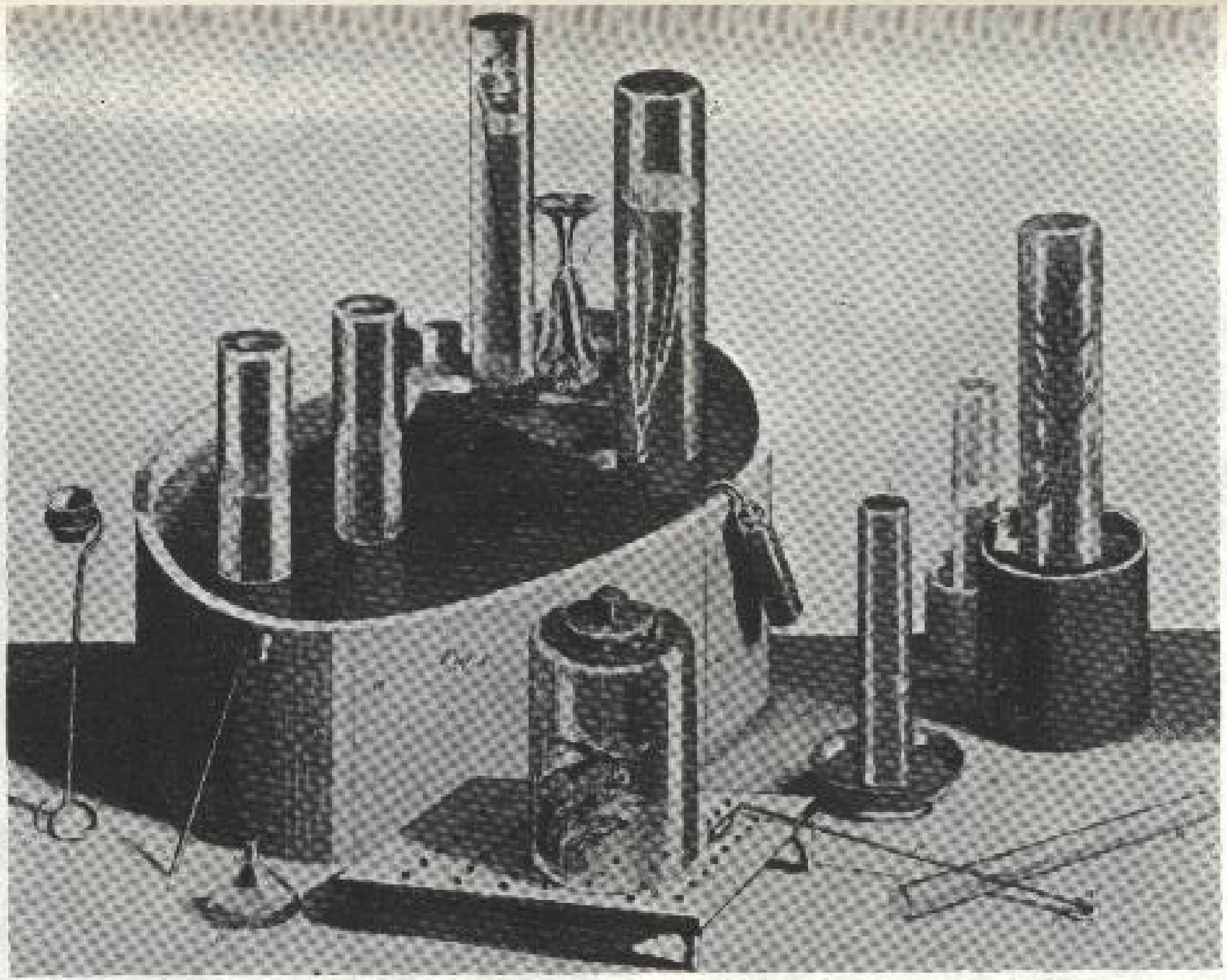


Fig. 35. The Pneumatic Trough

(*See p. 135*)

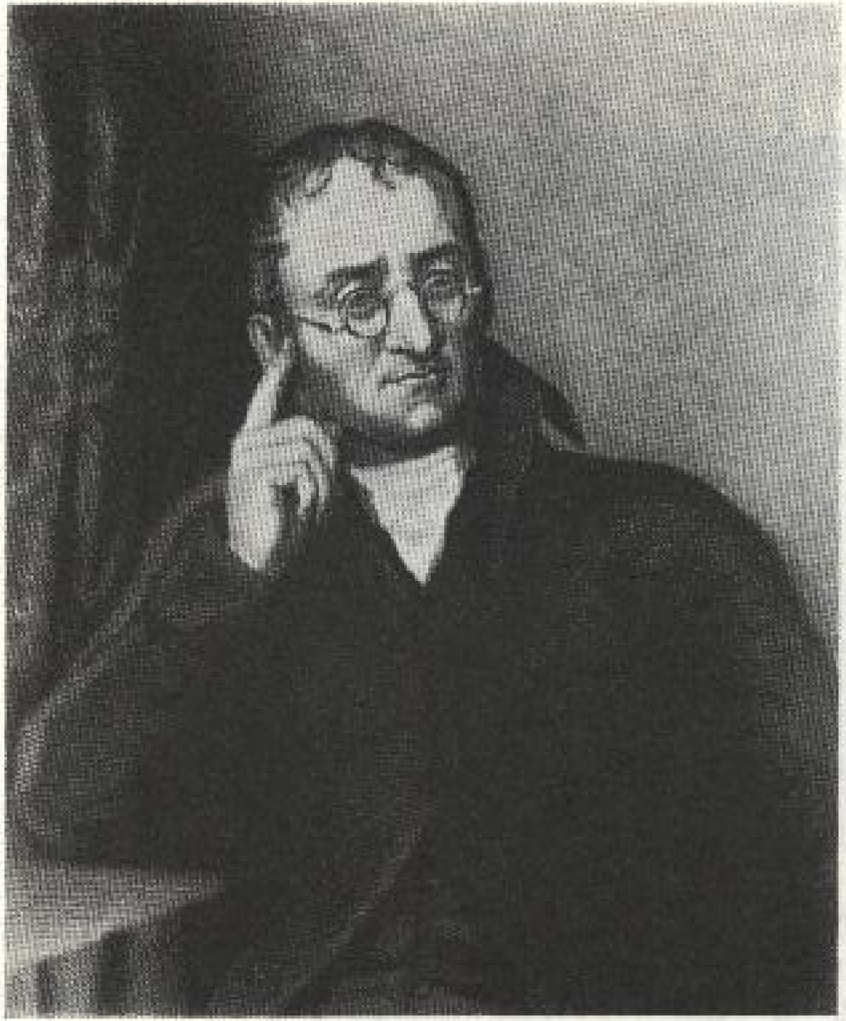


Fig. 39. John Dalton, 1766–1844
(*See p. 153*)

Fig. 40. Jöns Jacob Berzelius, 1779–1848
(*See p. 155*)

molecules of water. Secondly, from Avogadro's Hypothesis, it follows that 2 volumes of hydrogen combine with 1 volume of oxygen to yield 2 volumes of water, if the last-named is measured in the gaseous form of steam (the experiment being carried out at a temperature above the boiling-point of water). Thirdly, the atomic weights concerned being known to be $H=1$ and $O=16$, it is seen from the equation that 4 parts by weight of hydrogen combine with 32 parts by weight of oxygen to yield 36 parts by weight of water. The equation also bears out the conception of the conservation of matter, since the weights of the substances on both sides (those of the original and final substances) are equal.

A molecular formula also furnishes the percentage composition of the substance, provided that the atomic weights of the constituent elements are known. For example, the molecular weight of nitric acid, HNO_3, is $1+14+(16\times3)=63$. The percentage of nitrogen in the pure acid is thus $100\times14/63=22{\cdot}22$ per cent. Similarly, water (H_2O) contains 11·11 per cent. of hydrogen and 88·88 per cent. of oxygen by weight.

An almost unending series of important ramifications of the vast field of modern chemistry could be brought forward at this point; but perhaps one of the main streams of the development from about the mid-nineteenth century is best shown by taking a brief glance at attempts to classify the elements and the broad results accruing therefrom.

Classification and Nature of the Elements

The progress of chemistry in the first few decades of the Atomic Theory was marked, among other things, by the discovery of more and more elements, that is to say, of substances which it was found impossible to break down into simpler substances. Gradually, similarities became apparent between certain of the elements, and several attempts were made to group them into sets or families. It was noticed, for example, that the atomic weight of bromine (80) was roughly the mean of the atomic weights of the two similar elements, chlorine (35·5) and iodine (127); and there were other similar cases. Ideas of this kind became more precise after the application of Avogadro's Hypothesis, in 1858, had cleared up many uncertainties about atomic weights.

In 1863, Newlands, who held an appointment as chemist in a London sugar refinery, advanced his Law of Octaves. He pointed out that when the known elements were arranged in the order of ascending atomic weights, various elements showed a similarity in properties to elements standing seven, or some multiple of seven, places before or after them in the series. At that time, however, there were many gaps in the series of elements, and Newlands' enthusiasm was quenched by the cool, and even sarcastic, reception of his ideas.

A few years later, in 1869, the Russian chemist Mendeléeff (1834-1907) elaborated the same idea, and put forward the famous Periodic System of classifying the elements. He stressed the periodicity of properties, and explained a number of apparent discrepancies by assuming the existence of gaps in the series, owing to the presence in Nature of undiscovered elements. He even predicted their eventual discovery, and assigned properties to some of these unknown elements, '*eka*-aluminium, *eka*-silicon, and *eka*-boron,' which were afterwards strikingly verified by the discovery of the elements gallium, germanium, and scandium, conforming exactly to his predictions.

Dmitri Ivanovitsch Mendeléeff (Fig. 41), the most famous of all Russian chemists, was the youngest of fourteen children. He was born at Tobolsk, to which district his mother, a member of the old Russian family of Korniloff, belonged. Her husband's death left her in straitened circumstances; but in 1850 she removed to St. Petersburg and managed to launch her youngest son upon a course in mathematical and physical science at the Central Pedagogic Institute. After filling a number of minor teaching posts, he was able to study further at St. Petersburg, Heidelberg, and Paris. Eventually in 1866 he was appointed to a University chair of Chemistry at St. Petersburg. His brilliant lectures, with their freshness of thought, delighted his students and brought home to them that chemistry was really a science. It is significant, in view of his own work, that Mendeléeff defined a theory, in distinction from a hypothesis, as being a conclusion drawn from established facts and enabling new facts to be foreseen.

Mendeléeff's personal appearance was dominated by his abundant growth of hair, which he allowed to be cut only once a year, in the spring at the approach of warm weather. He was devoted to his mother, and with good reason, as he shows in the dedication of his celebrated work on *Solutions*, written in 1887: 'This investigation is dedicated to the memory of a mother by her youngest offspring. Conducting a factory, she could educate him only by her own work. She instructed by example, corrected with love, and in order to devote him to science she left Siberia with him, spending her last resources and strength. When dying she said, "Refrain from illusions, insist on work, and not on words. Patiently search divine and scientific truth." . . . Dmitri Mendeléeff regards as sacred a mother's dying words.'

By the middle of the twentieth century a total of ninety-two elements had been discovered in Nature, and an early

ELEMENTS

Helium	Lithium	Beryllium	Boron	Carbon	Nitrogen	Oxygen	Fluorine
He 4	Li 7	Be 9	B 11	C 12	N 14	O 16	F 19
Neon	Sodium	Magnesium	Aluminium	Silicon	Phosphorus	Sulphur	Chlorine
Ne 20	Na 23	Mg 24	Al 27	Si 28	P 31	S 32	Cl 35
GROUP							
O	I	II	III	IV	V	VI	VII

Fig. 42. Part of the Periodic Table of Elements

part of the so-called Periodic Table of the Elements, as it now stands, is shown in Fig. 42, which gives symbols, atomic weights, and group-numbers of the elements concerned:

Group O, unknown to Mendeléeff in 1869, consists of the rare gases of the atmosphere, helium, neon, argon, krypton, etc., which are distinguished by their extraordinary chemical inactivity. Group I is the family of 'alkali metals,' lithium, sodium, potassium, rubidium, etc.; these are soft silvery metals which tarnish (oxidise) quickly in air, and react vigorously with water, yielding hydrogen and a caustic (strongly alkaline) solution. Group VII consists of the halogen elements, of which fluorine, chlorine, bromine, and iodine—all of them non-metals—are common in naturally occurring compounds, such as fluorspar (calcium fluoride, CaF_2) and sodium chloride (common salt, NaCl).

These striking relationships naturally aroused much speculation regarding their fundamental cause. So far back as 1816, Prout had conjectured that all atomic weights were exact multiples of that of hydrogen, the atoms of other elements being formed by the condensation of hydrogen atoms in different numbers. This assumption of hydrogen as the protyle, or primary matter, of all elements, although of much interest, could not be substantiated. The accumulation of evidence showed that there must be some deeply rooted cause for the periodicity of properties; but no explanation was forthcoming until a considerable advance had been made in the sister-science of physics.

In 1897, J. J. Thomson (1856-1940), Cavendish professor of experimental physics in the University of Cambridge, in studying the phenomena attending the discharge of electricity through gases under extremely low pressures, discovered a particle of matter having only 1/1840th the mass of the hydrogen atom. This he recognised as the lightest of all known particles; identified it with a unit of negative electricity; and named it the electron. Extensions of these researches, carried out largely at Cambridge in the first part of the twentieth century, led to the gradual evolution of the theory of the electronic constitution of the atom, and thus of matter in general.

According in particular to the views of Thomson's successor at Cambridge, Lord Rutherford (1871-1937), and Bohr (b. 1885), professor of physics at Copenhagen, there grew up a picture of the atom as a positively charged nucleus surrounded by revolving electrons. The whole atomic structure is considered as an aggregation of positive and negative electrical units, known as protons and electrons, respectively. The mass of the atom lies almost entirely in its nucleus, which is supposed to consist of protons and neutrons. Since a neutron includes an electron as well as a proton it is electrically neutral. The excess of protons (over and above those of the neutrons) contained in the nucleus is exactly balanced by an equal number of electrons revolving about the nucleus. The number of this excess of protons (equal to the number of the revolving electrons) is known as the 'atomic number' of the element. The atomic number has acquired great significance as the serial number of an element in the revised periodic classification.

The free or so-called 'planetary' electrons are supposed to revolve in closed orbits around the nucleus, and to be arranged in shells or layers (also called levels). The number of electrons in the outermost shell is particularly important, since it determines the chemical character of the atom. These outermost electrons are called 'valency electrons,' and do not as a rule exceed 8 in number. Thus Newlands' Law of Octaves, scorned at the time, has a deep significance: it is an expression of the recurrence of chemical properties in intervals of octaves, owing to the building up of valency electrons from 1 to 8 in the progression along the octave. Thus, in Fig. 42, the lithium atom has 1 valency electron, beryllium 2, boron 3, carbon 4, nitrogen 5, oxygen 6, fluorine 7, and neon has the full complement of 8. Further, lithium, sodium, potassium, and the other 'alkali metals' each has 1 valency electron in its atom; and the atoms of fluorine, chlorine, bromine, and iodine each has 7. In general, each member of a natural family of elements has the same number of valency electrons in its atom, because the valency electrons determine the chemical character and reactivity of the atom. When an 'octet' of 8 valency electrons is built up in the outermost shell around the nucleus, a structure marked by great stability is reached, as in the rare gases, neon, argon, etc.

In another direction, as a consequence of these studies of atomic structure, it has become possible to bring about certain artificial transmutations of elements by causing changes to take place in the atomic nucleus. Indeed, some elements of high atomic weight, such as radium (226) undergo a slow spontaneous atomic disintegration, marked by the continuous liberation of large amounts of energy, in the form of heat. In 1945 it was found possible to bring about a rapid and complete 'nuclear fission,' on a large scale, of uranium of atomic weight 235, with the sudden liberation of colossal amounts of energy, in a so-called 'atomic explosion.'

The electronic constitution of the atom, and of matter in general, cannot be followed farther here. To the student of alchemy it brings echoes of the ancient doctrine of the Two Contraries, and of the later sophic Sulphur and sophic Mercury, now represented by the positive proton and the negative electron; of the Hermetic Androgyne, now figuring as the neutron; of Aristotle's idea of a primordial matter, linked with the alchemical belief in the unity of all things; of the undying faith of generations of alchemists in the possibility of metallic transmutation; and of Plato's view, conceived more than two thousand years ago, that Nature rests upon a mathematical plan, and that the ultimate realities must be sought in mathematics. Such fundamental and widely held conceptions, running like an unbroken thread through the whole history of human thought, may be observingly distilled into that sapient French saying, 'Plus ça change, plus c'est la même chose!'

X · THE RISE OF ORGANIC CHEMISTRY

Branches of Modern Chemistry

THROUGHOUT the ages, so far back as the Islamic period of alchemy, it had been recognised that some kinds of matter were of a mineral nature while others were associated with living organisms. Much later, the iatro-chemists, among them le Febure, Glaser, and Lemery, arranged their pharmaceutical preparations according to their derivation from animal, vegetable, or mineral sources. During the eighteenth century this division became more distinct, and eventually the great and growing number of substances known to the chemist were arranged in two main classes. One class comprised substances which were either found in, or could be prepared from, inanimate mineral matter: these were called inorganic substances. In the other class were placed all substances obtained from plant and animal organisms, and which therefore owed their origin to living or 'organised' matter: these were called organic substances.

'Inorganic Chemistry' therefore includes the study of such substances as the gases of the atmosphere; water; hydrochloric acid, sodium hydroxide (caustic soda), and other mineral acids and alkalies; metals and their oxides and salts; non-metals and their derivatives, such as sulphur, phosphorus, phosphoric acid, nitrogen, and ammonia.

Among typical organic compounds found in Nature are marsh gas and all the constituents of natural petroleums; acetic, lactic, tartaric, benzoic, and a very large number of other acids; carbohydrates, including sugars, starches, and celluloses; the constituents of plant and animal fats, and waxes; the proteins; organic bases, such as quinine, strychnine, and other alkaloids; indigo, alizarin, and other natural dyes; camphor, citral, and other constituents of the essential (fragrant and volatile) oils of plants; penicillin; and so on, in an almost endless variety. In due course it was found that all these natural organic compounds contain carbon as one of their constituent elements; also, as a corollary, that carbon stands alone among the elements by virtue of its phenomenal capacity for giving rise to endless multitudes of derivatives.

For a long time it was supposed that none of these plant and animal substances could be made artificially, and that their production was dependent upon life-processes and the operation of an imagined 'vital force.' This belief, which was held in the phlogistic era and accepted later by Berzelius and others, was undermined in 1828 by an experiment of Woehler, who prepared in the laboratory, without the intervention of any living matter, the substance urea. This white crystalline solid, discovered in urine by Rouelle in 1773, is one of the most typical products of animal metabolism. 'I can prepare urea,' wrote Woehler to his venerated master, Berzelius, 'without requiring a kidney or an animal, either man or dog.' Soon afterwards the English chemist, Hennell, prepared alcohol artificially. Laboratory syntheses of many other natural organic substances followed, and the idea of a vital force was abandoned.

However, these substances are so exceedingly numerous that it was found advantageous to keep the term 'organic' in use, especially as it began to be realised that the element carbon could give rise to further multitudes of compounds unknown in Nature. The term Organic Chemistry now comprehends all compounds containing carbon, whether of natural occurrence or solely man-made, such as, for example, chloroform, picric acid, synthetic dyes, sulpha drugs, and artificial fibres and plastics. 'Organic Chemistry' is thus the chemistry of the carbon compounds.

Chemistry is now so vast a subject that in the course of time it has thrown out still other branches. Of great importance is 'Stereochemistry,' or 'chemistry in space', which deals with the spatial arrangement of atoms within the molecule: this branch arose at about the middle of the nineteenth century (p. 182), and now permeates chemistry in general and organic chemistry and biochemistry in particular. 'Biochemistry,' in turn, may, like stereochemistry, be regarded as a ramification of organic chemistry: it deals with the chemical and physico-chemical processes of living plants and animals. Chemistry and physics together comprise physical science, and have therefore an extensive borderland: accordingly, another branch of chemistry, known as 'Physical Chemistry,' is concerned with the study of physical properties in relation to chemical constitution and chemical change.

Thus, organic chemistry forms a link between physical science and biological science; while inorganic chemistry is intimately bound up with geology, mineralogy, metallurgy, and more recondite fields of science, such as astrophysics. All branches of chemistry are closely interwoven with physics.

Both inorganic and organic chemistry have exerted, and continue to exert in increasing measure, a tremendous impact upon the development of modern civilisation. In almost every conceivable direction, ranging from agriculture and the great manufacturing industries to cosmetics and nylon stockings, applied chemistry enters into the operations and activities of everyday life; so that, quite apart from its intense intellectual appeal, chemistry, of all the branches of science, has contributed most to the necessities and amenities of modern life. To mention only a few of the industries depending upon the application of organic chemistry: from fats are manufactured soaps, glycerine, candles, paints, varnishes, linoleum, and margarine; industries based upon cellulose yield textiles, paper, guncotton, cordite, artificial silks, and power alcohol; and from coal tar arise dyes, drugs, perfumes, photographic chemicals, disinfectants, explosives, nylons, artificial rubbers, and plastics.

The Beginnings of Organic Chemistry

Organic chemistry, as a science, may be said to date from about the time of Woehler's artificial production of urea, in 1828. Of course, many natural organic materials were used from the earliest times, since they include all the fundamental types of foodstuffs and clothing materials (from fig-leaves onwards), as well as oils, gums, waxes, resins, perfumes, spices, dyes, and so forth, in lavish variety. Such typical processes of organic chemical technology as soapmaking and dyeing were known to the early civilisations, as was also baking and brewing (p. 8). Much later, by virtue of their special outlook, the iatro-chemists were much concerned with the chemistry of plant and animal products. Nevertheless, until the Atomic Theory had been put forward and established, early in the nineteenth century, the progress of organic chemistry had consisted of little more than a stumbling by chance upon new naturally occurring organic compounds; and here Scheele made a notable contribution by his discovery of many new organic acids and of glycerine (p. 133). Without an inspiring theory, no further development of the chemistry of these natural organic substances could well be expected.

Even after the establishment of the Atomic Theory, it was held for some time to be dubious whether some of the leading consequences of the theory could be applied to organic compounds; whether, for example, organic compounds conformed, like inorganic ones, to definite formulae. There seemed, indeed, to be a wide gulf separating the two divisions of compounds. In the first place, organic compounds were found to be invariably destroyed by heat, whereas many inorganic compounds sustained even the temperature of the blowpipe. Secondly, there came the question of number and diversity. The considerable number of inorganic compounds can be ascribed to the fact that they embrace (at the present time) all the derivatives of all the ninety-odd elements, except those of carbon. On the other hand, as Lavoisier and Berthollet showed, organic compounds are for the most part built up from four elements, namely, carbon, hydrogen, oxygen, and nitrogen. It follows that their enormous number and variety must be ascribed to the occurrence in organic chemistry of great molecular complexity.

In fact, it has been found that organic molecules range from such simple ones as CH_4 (methane), CH_2O (formaldehyde), $H_2C_2O_4$ (oxalic acid), through those of increasing complexity, such as $C_{12}H_{22}O_{11}$ (cane sugar), $C_{21}H_{22}O_2N_2$ (strychnine), and $C_{57}H_{104}O_6$ (a fat), to the enormous molecular structures of starches, celluloses, natural rubber, proteins, etc., numbering their atoms in thousands. In contrast to these stand the simple formulae of inorganic chemistry, such as $CaCO_3$ (calcium carbonate), NaOH (sodium hydroxide), H_3PO_4 (phosphoric acid), and $K_2Cr_2O_7$ (potassium dichromate).

A third great difference between organic and inorganic compounds was found in a phenomenon known as 'isomerism.' Woehler's preparation of artificial urea in 1828 had a twofold significance; for, besides what has been said above (p. 166), it confirmed a somewhat earlier observation that two distinct substances can have the same percentage composition, and, as was shown later, the same molecular formula. Urea, in fact, has the same percentage composition as ammonium cyanate: these two substances, which have widely different physical and chemical properties, have the common formula, CH_4ON_2. Berzelius, in 1830, coined the word 'isomerism' to denote this kind of relationship. Thus, isomers are compounds having the same molecular formula. Their number is often very large, and may theoretically in some cases run into millions. For example, there are more than 120 distinct substances now known which have the common molecular formula, $C_{10}H_{16}O$, and many others are theoretically possible; one of them is camphor, a crystalline solid, another is citral, a fragrant liquid found in oil of lemon. Isomerism, which is exceedingly rare in inorganic chemistry, is one of the most typical features of organic chemistry.

In spite of the above differences between inorganic and organic compounds, it began to be evident, through the analytical work of Berzelius from about the year 1815, that organic compounds, like inorganic ones, could be represented by definite formulae. Some years later, in 1831, Liebig introduced adequate experimental methods of determining the exact percentage composition of a large number of organic substances, and thenceforward organic chemistry attained the status of an exact science capable of mathematical treatment, as inorganic chemistry had become earlier through the work of Lavoisier.

The frequent occurrence of isomerism among organic compounds showed the overwhelming importance of molecular structure in this branch of chemistry; for it became evident thereby that the mode of arrangement of the atoms in the organic molecular edifice was no less important than their number and nature. Indeed, it is quite conceivable that the same assortment of atoms assembled in one way might furnish a beneficent drug, and when rearranged in another way might lead to the formation of a toxic compound.

The riddle of organic molecular structure took a long time and much work and thought to solve, particularly as the significance of Avogadro's Hypothesis was not realised until 1858 (p. 152). However, long before this, the 'dawn of a new day,' as Berzelius called it, came with a publication of Woehler and Liebig in 1832, in which they showed that a common association of atoms, which they termed a radical, could survive unaltered a series of changes brought about by chemical means in the other parts of the molecules concerned.

Liebig (1803-73) and Woehler (1800-82), who became great friends, exerted a profound influence upon the progress of organic chemistry during this period. It has been said that, about 1840, ambitious young chemists from all parts of the world 'used to flock either to the laboratory of Liebig at Giessen or to that of Woehler at Göttingen.' Both of these pioneering schools offered the novelty of public instruction in the practice of experimental chemistry and original chemical research, thereby inaugurating a new epoch in chemistry. 'We worked from break of day till nightfall,' wrote Liebig (Fig. 43). 'Dis-

Fig. 43. Justus von Liebig, 1803-73

sipation and amusements were not to be had at Giessen. The only complaint which was continually repeated was that of the attendant, who could not get the workers out of the laboratory in the evening when he wanted to clean it.'

A comparison of Figs. **30** and 44 shows the great change that had come over the chemical laboratory between 1747 and 1842, in which year Trautschold made the sketch of the Giessen laboratory which is redrawn in Fig. 44. Benches had now appeared, with cupboards, drawers, and shelves for reagent bottles; but there was no lighting or heating by gas, although the first gas company had been

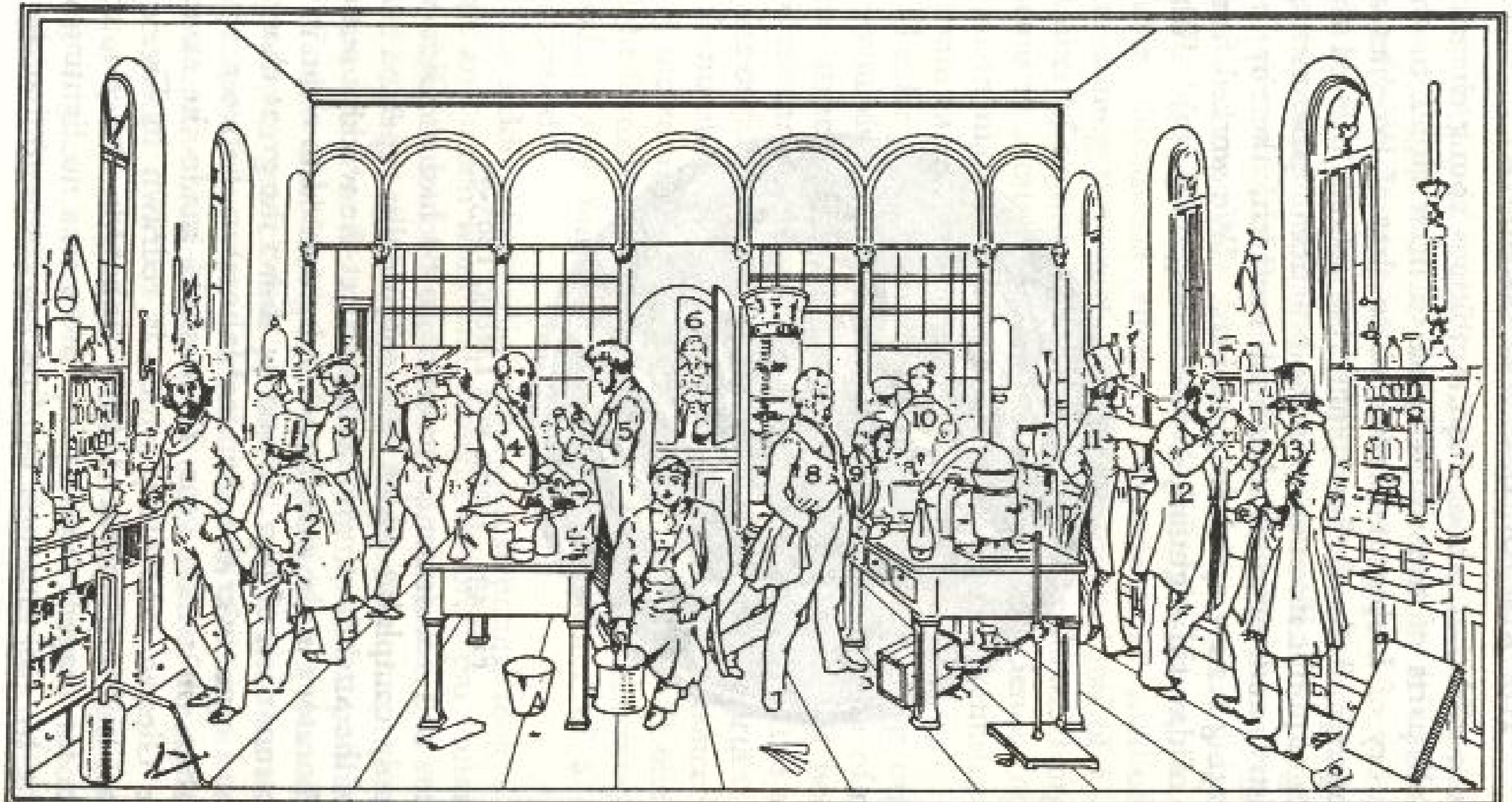


Fig. 44. Liebig's Laboratory at Giessen, 1842

incorporated in London in 1810. Spirit lamps and charcoal fires were used for heating; indeed, it was not until 1855 that Bunsen invented his celebrated gas-burner at Heidelberg, soon after he had left his old laboratory in the remnants of an ancient monastery for a new building in the Plöck Strasse, which became in turn a world-centre for ambitious young chemists.[1]

Work on the elucidation of organic molecular structure went through various developments until about 1850, by which time these delicate studies of molecular anatomy were bringing a definite molecular pattern into focus. Then came, in 1852, the 'Theory of Valency,' put forward by Sir Edward Frankland This theory regarded each kind of atom as possessing a certain valency, or capacity of combining with other atoms, which was expressible as a definite number; but the theory could not meet with a proper application until the significance of Avogadro's Hypothesis was recognised, in 1858. Before that time, if the atomic weight of carbon were taken as 6, the molecular formula of methane appeared to be C_2H_4, or perhaps CH_2, instead of CH_4, as it was seen to be when carbon was assigned its correct atomic weight of 12. It was in that year, 1858, charged with significance for the whole future of organic chemistry, that Kekulé advanced the fundamental theory of organic molecular structure.

Organic Molecular Structure

Among the numerous pupils of Liebig who became famous in the world of chemistry, Friedrich August Kekulé (1829-96) takes high rank. The notes of Liebig's lectures which he took as a student are still extant; they cover 346 pages of a neat and closely written script, with many small illustrative sketches. They are entitled 'Experimentalchemie vorgetragen von Prof. Dr. v. Liebig, 1848,' with the flyleaf inscription, 'A. Kekulé stud. chem.' Kekulé had entered the University of Giessen as a student

[1] *Humour and Humanism in Chemistry*, p. 248.

of architecture, but Liebig's brilliant lectures turned him from the gross to the molecular aspect of this art. Later, Kekulé migrated as a junior teacher to Bunsen's laboratory at Heidelberg, where, like Berzelius, he rigged up a laboratory in a room and kitchen of his dwelling.

Here, Kekulé carried out experimental work and concentrated his thoughts upon the fascinating and elusive problem of molecular structure. It has been written of him,[1] that, as Mark Twain might have said, although young, Kekulé was industrious: he lectured on organic chemistry; he prepared the experiments and also most of the lecture specimens himself; and often he closed his arduous day by sweeping out the classroom in readiness for the morrow's lectures. Kekulé's 'long, long thoughts' culminated in a flash of inspiration during a visit to London. As he related in a speech many years afterwards:

'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 (*Träumerei*), 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 even 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. . . . 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 *Structurtheorie*.'

These 'dream forms' led Kekulé to the 'Theory of Molecular Structure,' which he published in 1858. It

[1] *Text-book of Organic Chemistry.*

Fig. 41. Dmitri Ivanovitsch Mendeléeff, 1834–1907

(*See p. 160*)

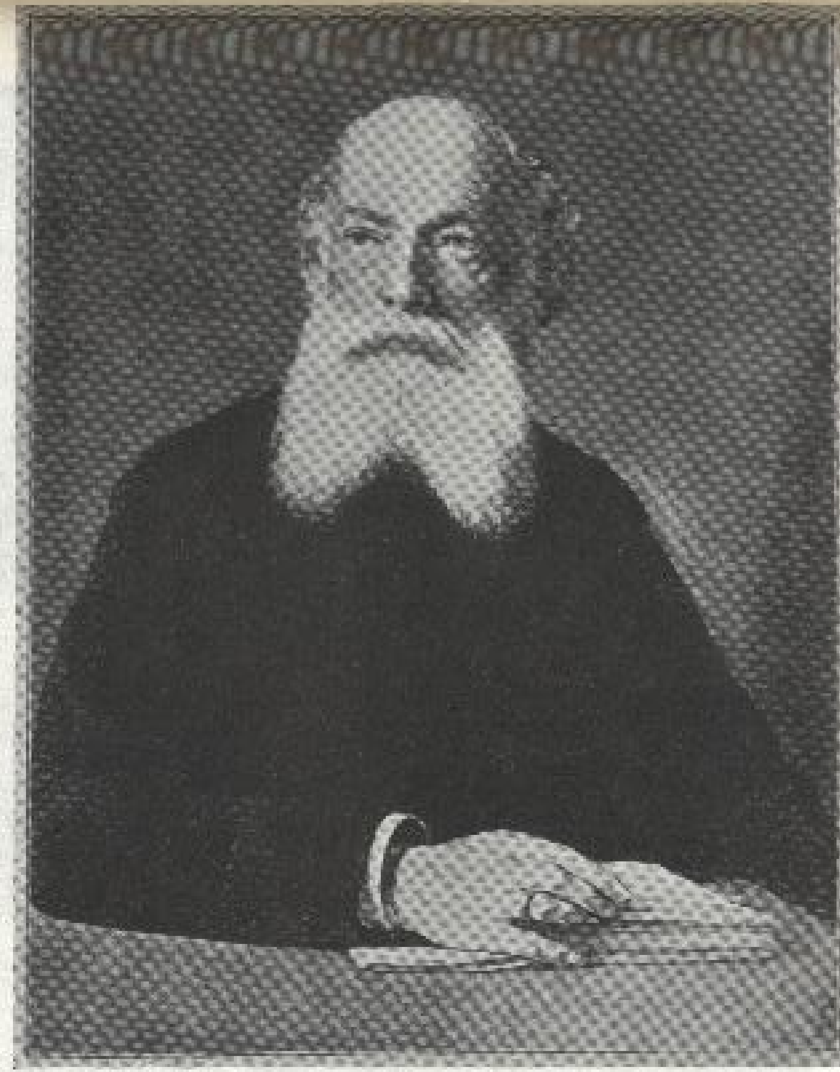


Fig. 45. Friedrich August Kekulé, 1829–1896, in his 61st year

(*See p. 180*)

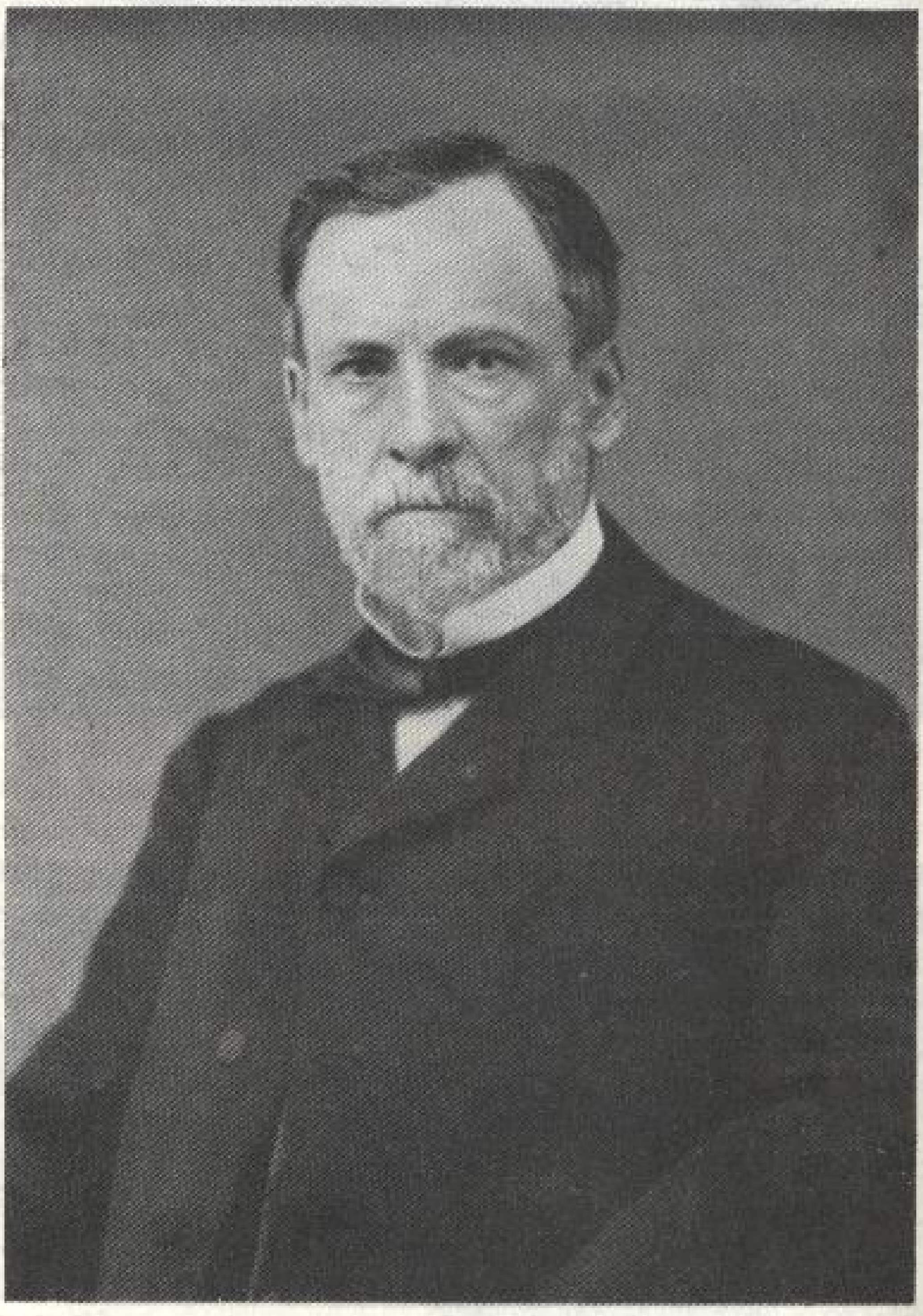


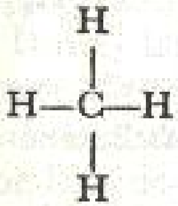
Fig. 47. Louis Pasteur, 1822–1895 (*c.* 1875)

(*See p. 187*)

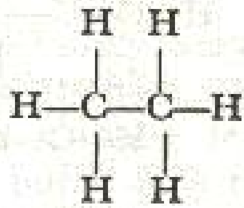
made two fundamental postulates: the quadrivalency of the carbon atom; and a capacity of carbon atoms for linking together to form chains. The organic molecule was thus pictured as containing a backbone of linked carbon atoms, to which other atoms, or groups of atoms (sometimes called radicals) could be attached, provided that each carbon atom maintained its valency of 4. The simplest examples are provided by hydrocarbons, which are composed of carbon and hydrogen only. Thousands of these substances are known, the two simplest being methane, CH_4, and ethane, C_2H_6.

Kekulé wrote in his original paper: 'The simplest and therefore most probable case of this union of carbon atoms is that in which one unit of affinity [valency, or valence] of the one carbon atom is combined with one unit of affinity of the other. Of the 2×4 units of affinity of the two carbon atoms, two are used up in holding the two atoms together; there therefore remain six which may be held in combination by atoms of other elements. . . . Thus the number of hydrogen atoms (chemical units) which may be combined with n carbon atoms is expressed by $n(4-2)+2=2n+2$.'

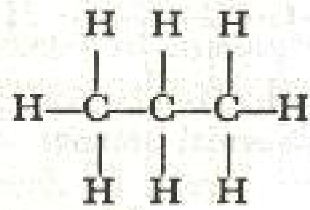
Methane and ethane are the two lowest numbers of a so-called 'homologous series' of hydrocarbons (occurring in natural petroleums), of which successive members have the molecular formulae, CH_4, C_2H_6, C_3H_8, C_4H_{10}, etc.; or, in general terms, C_nH_{2n+2}. In the light of Kekulé's theory these may be represented by so-called 'structural formulae,' which show how the component atoms of the molecules are linked together:



Methane



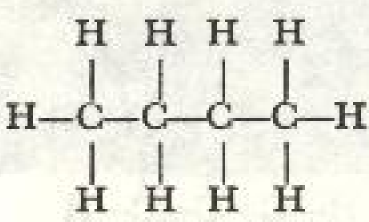
Ethane



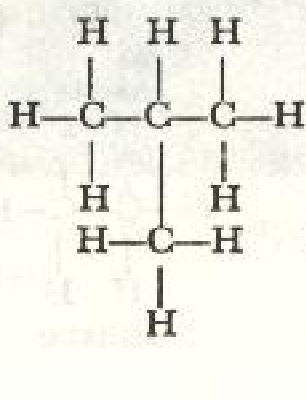
Propane

Organic compounds in general thus fall into large numbers of homologous series, in which the molecular weights form an arithmetical progression with a common difference of 14, corresponding to the common increment —CH_2—in the molecular formulae. There is no definite limit to the lengths of such carbon chains. In the above series of so-called 'paraffin hydrocarbons' a member $C_{100}H_{202}$ is known, but this does not represent an end term. Sometimes these carbon chains contain an enormous number of carbon atoms; the hydrocarbon of natural rubber, for example, has the molecular formula $(C_5H_8)_n$, in which n corresponds to several thousand carbon atoms of which four-fifths form the backbone of this long-chain molecule.

The homologous series of organic chemistry are of varied chemical character, since the attachments to the carbon atoms of the chains may include a great variety of other atoms or groups of atoms, such as the carboxyl group, —COOH, of organic acids, the amino-group, —NH_2, of many of the organic bases, the nitro-group, —NO_2, of nitro-compounds, etc. Moreover, the carbon chains can undergo branching, becoming more and more extensive and complicated as the size of the molecule increases. This process leads in turn to one of the many types of isomerism (p. 169) shown by organic compounds. This particular type is known as 'chain isomerism,' and in the paraffin series it sets in at a chain-length of four carbon atoms. Two distinct butanes exist, corresponding to the common molecular formula, C_4H_{10}, and to the two distinct structural formulae shown below:



Normal butane



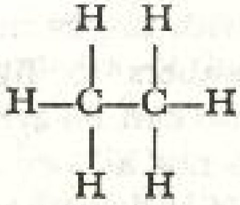
*iso*Butane

The isomers increase rapidly in number with increasing molecular complexity, some of the numbers being: C_5H_{12}(3), C_6H_{14}(5), C_7H_{16}(9). All of these can be synthesised in the laboratory, although they do not all occur in Nature. Ascending the homologous series still further, the numbers of isomers theoretically possible, but all of which no one has bothered to prepare, are: $C_{13}H_{28}$(802), $C_{18}H_{38}$ (more than 60,000), $C_{25}H_{52}$ (more than 86 million).

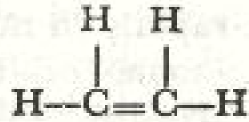
By a curious coincidence, to which there are a number of parallels in the history of science, in the year of Kekulé's publication (1858) a paper appeared in a French scientific journal expressing essentially the same view of organic molecular structure. This paper remained practically unnoticed, and the identity of the author was not discovered for half a century. The author proved to be a young, obscure Scottish assistant in Lyon Playfair's laboratory at Edinburgh, who suffered a sudden breakdown in health and was forced to retire from scientific work. 'In the history of organic chemistry,' wrote the German chemist Anschütz, in 1909, 'the sorely tried Archibald Scott Couper deserves a place of honour beside his more fortunate fellow-worker, Friedrich August Kekulé.' The theory of organic molecular structure is now often called the theory of Kekulé and Couper.

This theory accounts satisfactorily for one of the great divisions of organic compounds, known as 'open-chain,' or 'aliphatic' compounds, the latter name being applied because of the inclusion among such compounds of the important group of plant and animal fats and the derived 'fatty acids,' such as stearic acid, $C_{17}H_{35}.COOH$.

It may be added to this very slight sketch of an enormous range of types and individual compounds that two adjacent carbon atoms in a molecule may be united by a single bond, a double bond, or a triple bond, as shown in the following simple examples of hydrocarbons:



Ethane



Ethylene

Acetylene

A 'single bond,' shown by a short stroke, or often by a dot, indicates the mutual engagement, or satisfying, of one of the four valencies of each of the two carbon atoms concerned. In a 'double bond,' two, and in a 'triple bond,' three, of the valencies of each carbon atom enter into a similar alliance. Double and triple bonds are evidence of intramolecular strain, and hence of enhanced reactivity as compared with single bonds; and molecules containing them are said to be 'unsaturated.'

In Kekulé's day, and for long afterwards, there was no clear idea of the inner character of these so-called 'bonds.' Much later, with the introduction of the electronic theory of valency, they were interpreted in terms of valency electrons (p. 163), an interpretation which accounted satisfactorily for the existence of more than one type of bond. Throughout the monstrous regiment of organic compounds, the type *par excellence* is the so-called 'covalent bond,' which is created by each of the two atoms concerned contributing one valency electron in forming the linkage. To take the simplest example, a carbon atom, with its 4 valency electrons, can form a stable compound with 4 hydrogen atoms, each of which has 1 valency electron. The result is that the carbon atom becomes surrounded by a stable 'octet' of 8 electrons, binding it to the 4 hydrogen atoms and forming a stable molecule of methane, CH_4.

The second important type of valency bond, known as the 'electrovalent bond,' is concerned particularly in salt-formation, and does not apply to the great majority of organic compounds. The covalency is distinguished by the sharing of a pair of electrons, one of which is contributed by each of the linked atoms; but in the creation of an electrovalency an electron is actually transferred from a creditor atom to a debtor atom, thus leading to the formation of charged particles, or radicals, which tend to sever, or 'ionise,' especially in solution.[1]

The theory of Kekulé and Couper accounted satisfactorily for the molecular structure of the numerous open-chain substances; but it failed to embrace the whole field of organic chemistry. There remained an important and growing body of substances, referable at that time mainly to the coal-tar hydrocarbon, benzene, C_6H_6, which could not be brought into line with the original theory. This large division became known as 'aromatic' compounds, because many of its members were found to occur in various fragrant oils and aromatic spices, obtained from plants. The fundamental problem upon which Kekulé brooded for a further seven years, was to extend his theoretical conception so as to devise structural formulae accounting for certain peculiar chemical characteristics of these aromatic compounds. By this time (1865) Kekulé had been appointed to the chair of chemistry in the University of Ghent, and he was deeply immersed in writing a text-book of organic chemistry when a second revealing vision came to him. This is how he described it:

'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 the 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

[1] *A Direct Entry to Organic Chemistry*, p. 36.

spent the rest of the night in working out the consequences of the hypothesis.'

And so this vision of the Ouroboros Serpent (p. 25), the 'tail-eater' of Greece and ancient Egypt, a symbol 'half as old as time,' brought across the wide ocean of time to Kekulé the solution of one of the most baffling and most important problems of organic chemistry. 'Let us learn to dream, gentlemen,' Kekulé (Fig. 45) used to say to his students, 'and then perhaps we shall learn the truth'; but he was careful to add the note of warning conveyed in the words, 'let us beware of publishing our dreams before they have been put to the proof by the waking understanding.' Adolf Baeyer, one of the greatest of all organic chemists,[1] who had been a pupil of Kekulé at Heidelberg, and later succeeded Liebig at Munich, had caught from Kekulé one of the secrets of success in chemistry; for he used to say to his students: 'So viele Chemiker haben nicht genügend Phantasie (so many chemists suffer from a lack of imagination).'

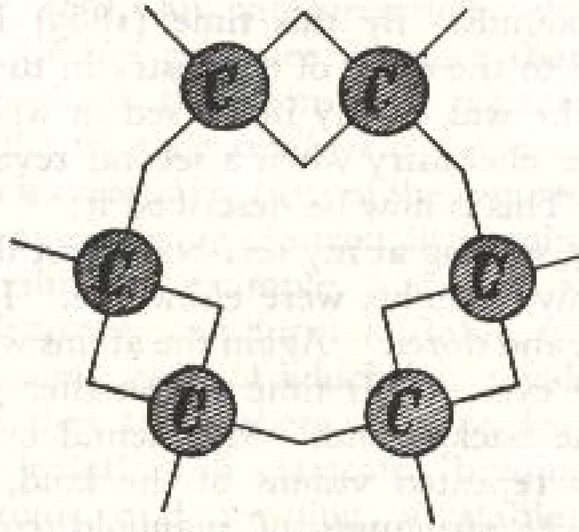
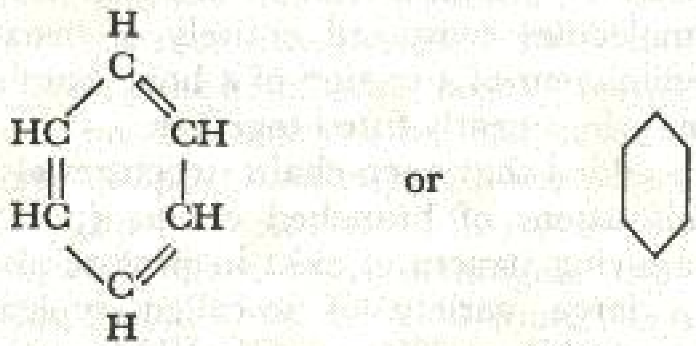


Fig. 46. Kekulé's Original Representation of the Benzene Ring

Kekulé's imagination had led him to the conception that assemblages of linked carbon atoms could form rings as well as open chains. The benzene ring consists of six carbon

[1] *Humour and Humanism in Chemistry*, p. 254.

atoms, each carrying one hydrogen atom, and linked to its two adjacent carbon atoms, according to Kekulé's original idea, by alternate single and double bonds. Fig. 46 shows Kekulé's original representation of the benzene ring, as given in his *Lehrbuch der organischen Chemie* (1866): the outstanding bonds provide for the attachment of one hydrogen atom to each carbon atom, and the alternate single and double connections between adjacent carbon atoms represent the single and double bonds of his formula. Nowadays, the benzene molecule, C_6H_6, is usually represented in one of the ways shown below, the plain elongated hexagon being merely an abbreviated version of the fuller formula:



The conception of the benzene ring has been called the crowning achievement of the linking of carbon atoms. Kekulé's fundamental ideas of organic molecular structure, that is to say, his conceptions of the carbon-chain and the carbon-ring, have led to developments in pure and applied chemistry that stand unsurpassed in the whole history of science.[1]

Later researches have shown that all organic Nature is based upon the carbon-chain and the carbon-ring, and that life itself depends upon the capacity of carbon atoms to link together so as to form the molecular chains and rings of acyclic and cyclic compounds, respectively.

Open-chain systems range from methane (CH_4), with

[1] See e.g. *A Direct Entry to Organic Chemistry*.

a single carbon atom in the molecule, to systems of thousands of carbon atoms, as, for example (p. 176), in the molecule of the natural rubber hydrocarbon $(C_5H_8)_n$. Ring-systems vary in size from three members to an undefined limit of certainly more than thirty.

Interspersed among the carbon atoms of these molecular chains and rings there are often atoms of other elements, especially nitrogen, oxygen, and sulphur, in that order of importance. This heterogeneity is particularly marked in the ring-systems of cyclic compounds.

Moreover, two or more rings may be joined or 'fused' together by sharing contiguous ring-atoms. Multitudes of polycyclic types of molecules are known, possessing many rings of various kinds. The structural formulae of polycyclic molecules composed entirely of benzene rings are often reminiscent of a section of a honeycomb, with all the hexagonal rings neatly fitted together.

When it is added that open-chain structures also include endless ramifications of branched chains (p. 176); that 'hybrid' chain-ring structures exist in profuse abundance; and that a large variety of so-called typical groups (—COOH, —CHO, $—NH_2$, $—CO{\cdot}NH_2$, etc.) may be substituted for a hydrogen atom at almost any position of a chain or ring carrying such an atom, some idea may be gained of the infinite variety of the organic molecular world.

Chemistry in Space

In Paris, in the year 1848, there was working at the École normale a young assistant named Louis Pasteur, who had been born of humble parents at Dôle, near Dijon, in 1822. He had undergone a training in science, and in order to perfect himself in crystallography he undertook the repetition of some work on the crystalline forms of certain salts of tartaric acid. At that time, tartaric acid was known in two isomeric forms, both obtainable from grape-juice, and related in a close and very puzzling way. One of them, ordinary tartaric acid (as also its salts), had the power of turning the plane of a beam of polarised light in a right-handed direction.[1] The isomeric acid, known as racemic acid, did not possess this property of 'optical activity,' since it allowed polarised light to pass through its solutions without deviation. It was already known that well-developed crystals of tartrates (salts of tartaric acid) were characterised by the occurrence upon their surface of small subsidiary facets, known as hemihedral facets. Moreover, an eminent German chemist, Mitscherlich, had stated in 1844 that sodium ammonium tartrate and sodium ammonium racemate had the same crystalline form; but that the tartrate deviated the plane of polarisation, while the racemate remained indifferent, or optically inactive. This statement aroused the attention of Pasteur, who thought that the crystals of the racemate should differ from those of the tartrate by lacking the hemihedral facets;[2] because throughout his work on the tartrates he had come to correlate their property of optical activity with the presence of these facets. The sequel is best related in Pasteur's own words:

'I hastened therefore to re-investigate the crystalline form of Mitscherlich's two salts. I found, as a matter of fact, that the tartrate was hemihedral, like all the other tartrates which I had previously studied, but, strange to say, the paratartrate [racemate] was hemihedral also. Only, the hemihedral faces which in the tartrate were all turned the same way, were, in the paratartrate inclined sometimes to the right and sometimes to the left. In spite of the unexpected character of this result, I continued to follow up my idea.

'I carefully separated the crystals which were hemihedral to the right from those hemihedral to the left, and examined their solutions separately in the polarising apparatus. I then saw with no less surprise than pleasure that the crystals hemihedral to the right deviated the plane of polarisation to the right, and that those hemihedral to the

[1] See e.g. *An Introduction to Organic Chemistry*, p. 185.
[2] *Text-book of Organic Chemistry*.

left deviated it to the left; and when I took an equal weight of each of the two kinds of crystals, the mixed solution was indifferent towards the light in consequence of the neutralisation of the two equal and opposite individual deviations.'

This observation, one of the most classical in the whole history of science, was at first received by the scientific world with astonishment, mingled with incredulity. The Académie des Sciences delegated the veteran physicist, Biot, the greatest authority of that time upon polarised light and its effects, to examine the plausible but startling story of this unknown young man. Again, Pasteur has left an account of what happened:

'He [M. Biot] sent for me to repeat before his eyes the several experiments. He gave me racemic acid which he himself had previously examined and found to be quite inactive to polarised light. I prepared from it in his presence the sodium ammonium double salt, for which he also desired himself to provide the soda and ammonia. The liquid was set aside for slow evaporation in one of the rooms of his own laboratory, and when 30 or 40 grams of crystals had separated he again summoned me to the Collège de France, so that I might collect the dextro- and laevo-rotatory [right- and left-handed] crystals before his eyes, and separate them according to their crystallographic character, asking me to repeat the statement that the crystals which I should place on his right hand would cause deviation to the right, and the others to the left. This done, he said that he himself would do the rest.

'He prepared the carefully weighed solutions, and, at the moment when he was about to examine them in the polarimeter, he again called me into his laboratory. He first put the more interesting solution, which was to cause rotation to the left, into the apparatus. Without making a reading, but already at the first sight of the colour-tints presented by the two halves of the field in the Soleil saccharimeter, he recognised that there was a strong laevorotation. Then the illustrious old man, who was visibly moved, seized me by the hand, and exclaimed: "My dear child, I have so loved the sciences throughout my life that this makes my heart leap with joy! (Mon cher enfant, j'ai tant aimé les sciences dans ma vie que cela me fait battre le coeur!)".'

It is strange that this dramatic scene, so charged with human interest, and rarely paralleled in the history of science, has never attracted the attention of any great artist.

Pasteur ascribed the existence of this so-called 'optical isomerism' to the formation of enantiomorphous molecules, that is to say, of molecules capable of existing in right- and left-handed forms, and related to each other as an object to its non-coincident image. His researches in this field of chemistry, carried out mostly between 1848 and 1858, led to the conclusion that organic molecules, like tangible objects, fall into two categories, designated by the terms symmetric and asymmetric (or non-symmetric).

A symmetric object, such as a teapot, gives a coincident image; also it possesses a plane of symmetry, that is to say, it can be divided into two similar halves, in this particular example by a plane directed at right angles to its base and bisecting the teapot midway through the spout and the handle. An asymmetric object, such as a hand, foot, glove, or shoe, gives a non-coincident image, that of a right hand being a left hand; also it has no plane of symmetry.

Pasteur's work showed that organic molecules also fall into these two categories. It follows that molecules must be three-dimensional, and not two-dimensional, or flat, as Kekulé's structural formulae might suggest. A flat object could not exist in right- and left-handed forms. If such a being as a Flatlander could exist, his two hands would be identical, and he would be unable to tell one from the other, or to decide whether a clock-hand were moving around in a 'clockwise' or 'counter-clockwise' direction. Since some molecules can exist in right- and left-handed forms, it follows that they must be extended in space of three dimensions; and therefore, by implication, that all molecules, whether asymmetric or symmetric, are three-dimensional and not flat.

Most of the simple organic molecules, such as those of methane, alcohol, oxalic acid, and benzene, are symmetric, and therefore do not exist in optically active, right- and left-handed forms. Beyond a certain degree of complexity however, the great majority of organic substances have asymmetric molecules and are therefore capable of existing in optically active forms. For example, all the natural carbohydrates and proteins are optically active and therefore possessed of asymmetric molecules, and the same may be said of the tissues and secretions of living plants and animals. In view of this, is it not surprising that the right- and left-handed forms of the same substance often differ very markedly in their physiological action.

It is a curious and very significant fact that, through the operation of a principle known as 'asymmetric synthesis,' Nature produces in most cases (although there are some exceptions with the simpler molecules) only one of the possible optically active forms. For example, glucose is known in Nature only in the right-handed or dextrorotatory form, although it has been synthesised artificially also in the left-handed form.

As Pasteur wrote, in 1860: 'If the mysterious influence to which the asymmetry of natural products is due should change its sense or direction, the constitutive elements of all living beings would assume the opposite asymmetry. Perhaps a new world would present itself to our view. Who could foresee the organisation of living things if cellulose, right as it is, became left; if the albumin of the blood, now left, became right? These are mysteries which furnish much work for the future, and demand henceforth the most serious consideration from science.'

Pasteur (1882-95) became the founder of stereochemistry, or 'chemistry in space,' which deals with the spatial arrangement of atoms in combination. After a century of research many of the ramifications and implications of this wide field of science, of equal importance in organic chemistry and biochemistry, still remain to be explored. But the foundation of stereochemistry was only the beginning of Pasteur's scientific work. Outstanding in his versatility, this great paladin of science passed on from stereochemistry to fermentation, pathology, and in particular to investigations showing that diseases could be induced by micro-organisms; and this work led in turn to the introduction of antiseptic surgery and immunisation. Huxley said that, in terms of money alone, Pasteur's work would have met the whole cost of the French war indemnity of 1870 (amounting to 5000 million francs). Louis Pasteur (Fig. **47**) was one of the greatest of Frenchmen and one of the most human and humane of scientists. He gained the affection and reverence of all. Osler said of him that he was the most perfect man that ever entered into the kingdom of science.

Pasteur was unable to interpret his ideas in precise terms of molecular structure, because Kekulé's theory of molecular structure, leading to structural formulae, had not been put forward at the time of Pasteur's experiments. With the advent of Kekulé's theory it became possible, during the next few years, to examine the structural formulae of the tartaric and lactic acids, and of various other substances which were known to exhibit optical activity. As a result, it was found that the molecules of all these substances assumed an asymmetric form—or 'configuration,' as it is usually called—when their flat Kekuléan representations were converted into three-dimensional ones, according to a very simple principle. This principle was embodied in the 'Theory of Molecular Configuration,' which was advanced independently and almost simultaneously in 1874 by the French chemist Le Bel, and the Dutch chemist, van 't Hoff.

The flat Kekuléan formulae conveyed tacitly that the carbon atom lay at the centre of a square, with the four attached groups occupying its corners (Fig. 48). In other words, the four valencies of the carbon atom were pictured as extending to the corners of a square having the carbon atom at its centre. The later theory of molecular configuration amounted essentially to a modification, or extension, of Kekulé's theory, for it embodied the two postulates of the quadrivalency of the carbon atom and the linking of carbon atoms, and added to them a third postulate of the tetrahedral environment of the carbon atom.

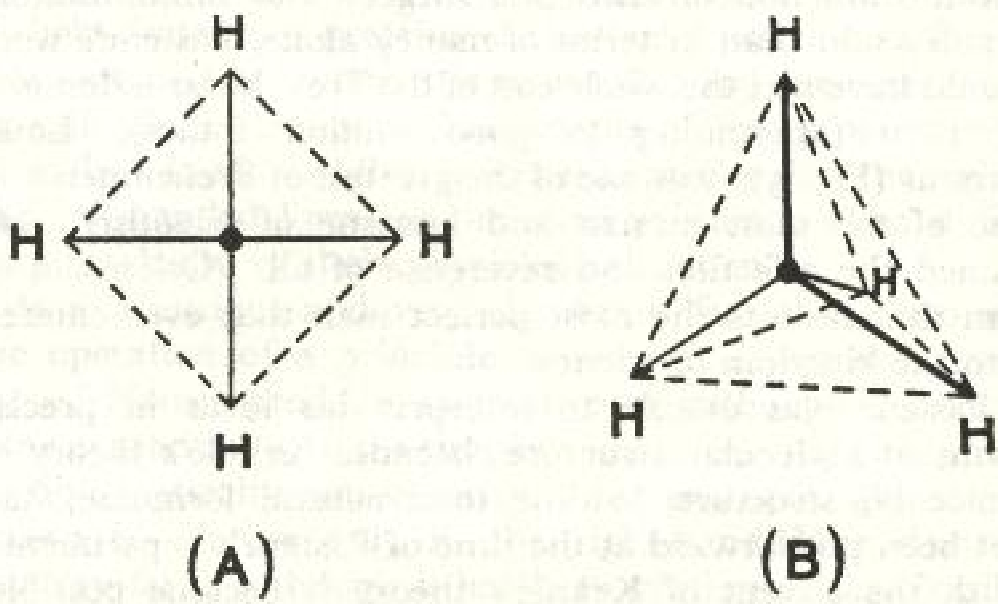


Fig. 48. Plane and Tetrahedral Representations of Methane, CH_4

This means that the four atoms, or groups of atoms, attached to a carbon atom are visualised as distributed about it in tri-dimensional space. Thus, the carbon atom lies at the centre of the tetrahedron, with the four valencies extending to the four solid angles of this solid figure, as shown in Fig. 48(B) for methane, CH_4.

The tetrahedral configuration of methane is obviously symmetrical; but when the four groups at the solid angles of the tetrahedron are all of a different kind (*Cabcd*), the figure becomes asymmetric. Fig. 49 illustrates the simple example of lactic acid, a substance known to exist in right- and left-handed forms, distinguished by their respective dextro- and laevo-rotatory effects on polarised light. In the lactic acid molecule, $CH_3 \cdot CH(OH) \cdot COOH$, the four groups attached to the central carbon atom are all different, being (*a*) CH_3, (*b*) H, (*c*) OH, and (*d*) COOH. A carbon atom to which four different kinds of groups are attached is called an 'asymmetric carbon atom.' The presence of such an atom in a flat Kekuléan structural formula is a criterion of the asymmetry of the whole molecule, and the consequent possibility of the substance existing in right- and left-handed (or enantiomorphous) forms. The asymmetric

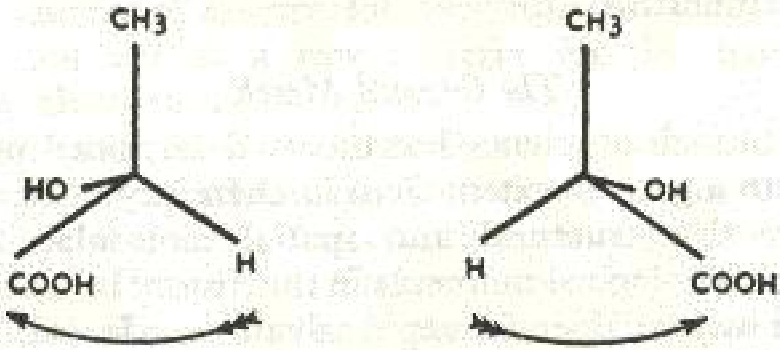


Fig. 49. Molecular Configurations of the Two Optically Active Forms of Lactic Acid

carbon atom is situated at the centre of each of the two configurations shown in Fig. 49, and the arrows show the clockwise and counter-clockwise disposition of the four attached groups.

The theory of molecular configuration is essentially a fuller expression of Kekulé and Couper's theory of molecular structure, in that it represents the structural formula in three dimensions instead of in two. For many ordinary purposes it is still sufficient to use the Kekuléan structural formulae; but for the finer aspects of organic chemistry and biochemistry it has become increasingly necessary to refer to the spatial configuration of the molecule. Stereochemistry, indeed, permeates the whole of the vast body of organic nature.

It has been pointed out elsewhere[1] that the expansion of

[1] *Text-book of Organic Chemistry.*

the Atomic Theory into the theories of molecular structure and molecular configuration provides a classical example of the gradual evolution of a scientific theory. Each successive stage of the theory defined a limited problem, the solution of which opened the way for a further advance; until the attainment of a position from which (to adapt some words of Sir John Herschel, referring to the still unseen planet, Neptune) we see the organic molecule 'as Columbus saw America from the shores of Spain. Its movements have been felt trembling along the far-reaching line of our analysis with a certainty hardly inferior to ocular demonstration.'

The Onward March

In no branch of science has theory determined practical progress to a greater extent than in chemistry. In organic chemistry the structural and spatial molecular theories came at psychological moments in the history of the science, when the way lay open for rapid advances. It was in 1856, only two years before the publication of Kekulé's theory, that an eighteen-year-old English student, William Henry Perkin (1838-1907), working during the Easter vacation in his 'rough laboratory at home,' discovered mauveine, the first synthetic organic dyestuff to be applied in dyeing. His synthesis of this dye from impure aniline, as a result of experiments aimed at the synthesis of quinine, became the herald of an enormous stream of work on synthetic coal-tar derivatives which ran in full flood throughout the next half-century. Without the guidance of Kekulé's benzene theory this great expansion would have been impossible.

From a few 'primaries' actually present among the numerous constituents of coal-tar—notably benzene, toluene, phenol, naphthalene, and anthracene—were prepared, as time went on, several hundred 'intermediates,' such as aniline from benzene, benzaldehyde from toluene, and phthalic acid from naphthalene. These led in turn, through the application of a variety of chemical processes, to the synthesis of thousands of purely artificial dyes, drugs, explosives, disinfectants photographic developers, and many other useful kinds of fine chemicals.[1] During the half-century after Perkin's day, certain coal-tar constituents were brought into use in the manufacture of nylons, synthetic rubbers and plastics, and other substitutes for age-old natural materials such as wood, glass, and natural fibres. Such work still continues. Moreover in the present century the great deposits of natural petroleum are undergoing an increasing development not only as sources of energy for heating, lighting, and locomotion, but also as a raw material for the manufacture of useful chemicals.

Concurrently with the synthesis of purely artificial substances from coal-tar, much work was being devoted to unravelling the molecular constituents of natural organic substances. Here, the German chemist, Emil Fischer (1852-1919) stood out as a master. His elucidation of the molecular constitution of sugars and their subsequent synthesis, which he began in the 1880's, would have been impossible without the guidance of the Space Theory of Le Bel and van 't Hoff. From this classical series of investigations he passed on to explore the molecular mysteries of the uric acid derivatives and the proteins. Other organic chemists took up similar work upon such important groups of compounds as the natural dyes, the pigments of flowers and leaves, the alkaloids, hormones, vitamins, constituents of the fragrant oils of plants, and many series besides.

With the deciphering of so many natural molecular types, it became possible to discern certain general structural relationships, including the recognition of standard patterns forming variations upon fundamental molecular themes. Hand in hand with the molecular diagnosis of natural organic compounds went very often their artificial

[1] *A Direct Entry to Organic Chemistry*, p. 229.

synthesis. These advances opened the way in turn to the practical realisation of artificial variations upon natural molecular themes, leading to improved dyes, drugs, rubbers, and many other useful substances with molecular structures based upon natural models.[1] The artificial rubber, neoprene, for example, is a synthetic variant of natural rubber in which the methyl group ($-CH_3$) attached to every fourth carbon atom in a long chain of thousands of such linked atoms in the natural molecule is replaced by a chlorine atom ($-Cl$) in the artificial molecule. As another example, the macromolecules of the purely artificial fibrous nylons are variants of structures found in natural protein molecules.

Well may the organic chemist, in his advance from the simple molecule of methane to the gigantic macromolecules of natural celluloses and proteins and of artificial fibres and plastics, exclaim with the poet:

All experience is an arch wherethro'
Gleams that untravell'd world, whose margin fades
For ever and for ever when I move.

Envoi

Much has that devotional procession 'travell'd in the realms of gold' from prehistory and the ancient civilisations, adown the long ages through alchemy, to modern chemistry; yet the tenor of that long travail found eloquent expression nearly two thousand years ago in some words of Lucretius:

'Ships and tillage; walls, laws, arms, roads, dress and all such like things; all the prizes, all the elegancies, too, of life, without exception; poems, pictures and the chiselling of fine-wrought statues: all these things, practice, together with the acquired knowledge of the untiring mind, taught men by slow degrees, as they advanced on the way step by

[1] *A Direct Entry to Organic Chemistry*, p. 204.

step. Thus time by degrees brings every several thing forth before men's eyes, and reason raises it up into the borders of light; for things must be brought to light one after the other, and in due order in the different arts, until these have reached their highest point of development.'

GLOSSARY

For terms explained in the text, reference should be made to the Index. It has not been considered necessary to include uncommon words or names to be found in ordinary dictionaries.

Alcaline salt of tartar, potassium carbonate. See also *sal tartre*.

Alembic, still-head, or upper part of a still (also *limbeck*, or *helm*, *q.v.*).

Antimony, strictly, metallic antimony; but alchemically, stibnite (native antimony sulphide).

Aqua vitae, aqueous alcohol concentrated by distillation; also *whisky*.

Argent-vive, quicksilver, mercury; sometimes regarded by alchemists as vivified ('quick') or mobile silver.

Argoyle, argol, or tartar, separating in wine-vats and consisting of impure potassium hydrogen tartrate (cream of tartar).

Asymmetric, non-symmetric; giving a non-coincident mirror-image, like a glove or shoe.

Asymmetric carbon atom, a carbon atom which is attached to four different kinds of atoms or groups, thus, *Cabcd*.

Athanor, an alchemical furnace, used especially for heating the sealed Vessel of Hermes.

Balneo, bath (of water, sand, cinders, etc.) for heating an immersed vessel.

Bolt-head, a round-bottomed flask with a long neck (also *matrass*).

Calx, oxide; *calx vive*, quicklime.

Ceration, the softening of a hard solid to a wax-like consistency.

Chymist. See *spagyrist*.

Crosslett, crucible.

Cucurbite, or *gourd*, the lower part of a still, containing the liquid to be distilled, and made of glass or earthenware.

Cupel, a shallow cupped receptacle made of a porous and infusible material such as boneash.

Cupellation, heating in air in a cupel, as in the refining of argentiferous lead, whereby the lead oxide is absorbed in the porous material of the cupel, leaving pure silver.

Dephlogisticated air, oxygen.

Dextro-rotatory, an adjective applied to a material which when traversed by a beam of polarised light (*q.v.*) turns or rotates the plane of polarisation in a right-handed direction.

Fixation, the process of converting a volatile substance into a non-volatile one which is able 'to abide and sustain the fire.'

Fixed air, carbon dioxide, because of its presence (in a combined state) in solid chalk, etc.

Glare of an ey, white of an egg.

Gourd, same as *cucurbite* (*q.v.*).

Helm, the upper part of a still, so called from its resemblance in shape to a helmet.

Inflammable air, hydrogen.

Laevo-rotatory, an adjective applied to a material which when traversed by a beam of polarised light (*q.v.*) turns or rotates the plane of polarisation in a left-handed direction.

Lunary, lunaria or moonwort (*Botrychium lunaria*), a plant associated with the crescent moon because of the shape of its leaves, and known to the alchemists also as *Martagon*.

Lute, a cement used in closing the apertures and joints of apparatus, whence perhaps the saying, 'a rift in the lute.'

Macromolecule, a very large molecule, often composed of thousands of atoms.

Magnesia, strictly, magnesium oxide; but alchemically, a vague term including such diverse substances as pyrites, pyrolusite, magnetite, and possibly magnesia itself.

Molecular configuration, a tridimensional representation of the structural formula (*q.v.*).

Molecular formula, a chemical expression showing the numbers of the various kinds of atoms in the molecule of the substance concerned, e.g. $C_{10}H_{16}O$, camphor; $C_{21}H_{22}O_2N_2$, strychnine.

Optically active, deviating, or rotating, the plane of polarised light (*q.v.*).

Pelican, a vessel for circulatory distillation, with two side-arms and having an imagined resemblance to the bird of this name (Fig. 9).

Phlogisticated air, nitrogen.

Polarimeter, an instrument for measuring the extent of the rotation of the plane of polarised light (*q.v.*) by an optically active substance (*q.v.*). Also *polariscope* or *saccharimeter*.

Polarised light, light in which the vibrations are confined to one plane perpendicular to the line of advance of the beam (and known as the plane of polarisation of the light).

Projection, the ultimate transmutative operation, in which a small amount of the Stone (powder of projection) was thrown upon the hot molten metal (lead, etc.) to transmute it into silver or gold.

Quadrivalent, a term applied to an atom (notably of carbon) having a valency (*q.v.*) or combining capacity of 4.

Receiver, a vessel, such as a flask, catching the distillate from a still.

Regulus of antimony, metallic crystalline antimony.

Retort, a globular vessel of glass or earthenware, provided with a tapering tubular stem and used in distillation, a receiver (*q.v.*) being fitted to the end of the stem.

Sal armoniak, ammonium chloride (originally *sal armeniac*, from its occurrence in Armenia, changed later to *sal ammoniac*, owing to its confusion with natron, or sodium sesquicarbonate, found near the temple of Jupiter Ammon in Libya).

Sal tartre, potassium carbonate (obtained by heating *tartar* or *argoyle*, *q.v.*).

Spagyrist, medico-chemist, iatro-chemist (sometimes *chymist*), follower of Paracelsus.

Structural formula, a representation of a molecule showing how its constituent atoms are linked together (acting as a kind of plane map of the molecule).

Sublimate, a solid material obtained by the condensation upon a cold surface of a vapour arising directly (without fusion) from a heated solid.

Tervalent, a term applied to an atom (e.g. of nitrogen) having a valency (*q.v.*) or combining capacity of 3.

Univalent, a term applied to an atom (e.g. of hydrogen) having a valency (*q.v.*) or combining capacity of 1.

Valency, or *Valence*, the combining capacity of the atom of an element, expressed numerically (and consisting of a small whole number); e.g. the valency of the carbon atom is 4, and so it may combine with 4 univalent hydrogen atoms (in methane, CH_4), or with 2 univalent hydrogen atoms and one bivalent oxygen atom (in formaldehyde, CH_2O), etc.

Vitriol, a shining crystalline body, such as *blue vitriol* (copper sulphate), or *white vitriol* (zinc sulphate). (*Oil of vitriol*, sulphuric acid.)

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FROM ALCHEMY TO CHEMISTRY

JOHN READ

"Chemistry, in particular, is capable, when suitably presented, of making a strong appeal to the intelligence and the imagination; for, as the following pages are intended to show, it is the most romantic of all the branches of science; and in its variegated history, stretching back through unnumbered generations of alchemists into an indefinite past, its present votaries have (if they but knew) a richly human and humanistic heritage."—Preface

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