Chemical Symbols and Formulæ.¹

By Sir JAMES WALKER, F.R.S.

SYMBOLS are both an aid and an obstacle to thought. Their brevity and simplicity may help us, working according to a fixed system, to perform mental operations which without their aid might be practically impossible. Their generality too may, as in algebra, enable us to solve thousands of problems in one. On the other hand, we sometimes find in science a system of symbols which, at first of great value, may in virtue of its very success so warp our thought or limit our mental outlook as to constitute a real hindrance to scientific progress. There is always the danger, arising from our familiar and constant use of the symbol, either of forgetting what it properly symbolises, or of confusing the symbol with the thing symbolised.

The function of the symbol is a practical one; in Mach's phrase, it is to effect economy of thought, and it is precisely because mankind at large is so economical of thought that the dangers of symbolism originate. The danger, however, must be faced by the student of chemical science, for without symbols systematic advance is impossible: the symbols are based on a theory and permit the representation of that theory in detail.

If we examine the practical requirement of a satisfactory system of symbols, we shall find that the system must be simple in itself and simple to operate. Consider the Roman schoolboy confronted with the problem of multiplying MCMXXIII by CXLIV. The system of notation is not too complicated, but to operate with it is practically impossible. To perform his task he must abandon the symbolism and have recourse to concrete objects—the fingers or an abacus. The Arabic notation, on the other hand, with its consistent valuation by position and the introduction of a symbol for zero, enables us, once we have passed the barriers of the addition and multiplication tables, to perform arithmetical calculations of all kinds with ease and speed. It is simple in itself and simple to operate.

The same requirements are essential to a system of chemical symbols. The first symbols, those for the metals known to the ancients, indicated nothing but their supposed association with the planets and the gods ruling them. Thus the solar disk stood for gold, the lunar crescent for silver, the mirror of Venus for the Cyprian metal copper, and so on. Towards the end of the eighteenth century we see the beginnings of our present system of elementary symbols. Hassenfratz and Adet (1787) used for the non-metals straight and curved lines which could be combined together (much as in phonetic shorthand) to represent the qualitative composition of compounds. The symbol for a metal was a circle, and to distinguish one metal from another the initial of its Latin name was written within the circle—thus (Sb) was the symbol for antimony.

Dalton used for metals and non-metals alike only circular symbols, doubtless to represent spherical atoms, and in his hands the symbols assumed a quantitative significance based upon his atomic theory. For the simple non-metals these symbols were arbitrarily

chosen, O representing an atom of oxygen, H an atom of hydrogen, N an atom of nitrogen, and so on. For the metals he adopted the same device as Hassenfratz and Adet, using, however, the English instead of the Latin names, so that for example (L) represented an atom of lead. Compounds could be represented by the juxtaposition of the elementary symbols, which now gave, not only the qualitative, but also the quantitative composition of the compound. Thus, for Dalton, water was represented by the symbol HO, denoting the combination of 7 parts of oxygen with 1 of hydrogen.

Berzelius (1815) took the final step by using Latin initials for all the elements, dropping the circles which had surrounded them, and employing affixed numerals to indicate the number of times the symbol had to be repeated. It is true that Berzelius spoiled the uniformity of his system by using a special dot symbol for oxygen and writing such formulæ as $\dot{S}$ for sulphur trioxide. These dotted symbols, however, found little favour except amongst mineralogists, and gradually passed out of use. The disuse of the circles is not without significance—the symbol to Berzelius represented a combining weight rather than a concrete atom, and the dual quantitative use persists in the interpretation of symbols to-day. The symbol C stands for one atom of carbon or "twelve parts by weight" of carbon. So we may say that more than a hundred years ago a system of formulation had been reached which, with minor alterations, is in use at the present time for the representation of elements and the composition of compounds, and is never likely to be superseded. It is uniform, plain, and simple in itself, and simple to use in the equations representing chemical change.

The purely compositional formulæ, however, fall far short of expressing what calls for expression in various classes of chemical compounds: action and structure have to be considered as well as composition. The dualistic formulæ of Berzelius illustrate early attempts in this direction. The formula of sodium sulphate is not written empirically as Na_2SO_4 , but dualistically as Na_2O, SO_3 . This formula indicates *inter alia* that the sodium and the sulphur belong to two essentially different parts of the compound. The modern electrochemical dualism writes Na_2SO_4 , again indicating the same division of a positive from a negative portion. In organic chemistry the representation of structure by means of formulæ achieved success by the clear recognition of valency—in particular, the quadrivalence of the carbon atom. At this point of development the notion of the atom as structural unit becomes indispensable.

The valency of an element on its experimental side is in essence a numerical conception. We divide a weight by a weight, namely, the atomic weight by the equivalent weight, and obtain in consequence a mere number. When we pass from element to atom, however, the conception undergoes a transformation, and receives a concrete meaning. The valency of an atom may be interpreted as its capacity for combining with other atoms, again a numerical conception, but one

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leading directly to a symbolism and indirectly to a mechanical interpretation. Each atom is conceived as having a definite number of places for the attachment of other atoms, and as the number is in each case small we can conveniently represent it in a graphic symbol.

It is not without interest to look back to the origin of graphic or constitutional formulæ and see the beginnings of our conventional system. Couper and Kekulé, the originators of the idea, suggested systems widely differing from each other. Couper (1858) symbolised acetic acid as follows,

in appearance a near approach to present-day usage if we allow for the fact that he assumes $\text{O}=8$ and $\text{C}=12$. The manner of linking of various atoms is indicated, but their valency is not clearly symbolised. Kekulé's graphic formula (1859) for the same substance is shown below.

Acetic Acid.

(Kekulé.)

(Loschmidt.)

The valency is satisfactorily represented, but the linkage of the atoms is confused. Only atoms touching in a vertical line are supposed to be directly linked. The system is cumbrous, and Kekulé himself used it but sparingly. For branched chains it becomes impracticable.

Loschmidt (1861) devised a clear logical system which, although he formulated by its means hundreds of compounds, some of a very complex nature, found no favour amongst chemists. His symbol for acetic acid is given in the figure. Here linkage and valency are adequately represented, but the atomic symbols are arbitrary, and the system, like Kekulé's, is cumbrous to use.

Simultaneously with Loschmidt, Crum Brown (1861), although he was unaware of Couper's work, used a symbolism resembling his, and practically identical with that in current use. He writes glycol as follows :

Here valency and linkage are clear, and the atomic symbols are no longer arbitrary. Wurtz in 1864 gave the following formula (I.) for the same substance :

The line of development of modern graphic formulæ, | conception of number of equivalents. In 1866

then, is through Couper, Crum Brown, and Wurtz, and not through Kekulé or Loschmidt. The reason for the preference shown by chemists is that the symbolism adopted is more obvious, simpler to use, simpler to reproduce, and easily adaptable to all organic compounds.

There is a dual character in our graphic formulæ which it is important that we should realise. Let us begin with the graphic symbols of the elements, thus :

$\text{H}-$, $-\text{O}-$, $-\text{C}-$, where each short line represents a

unit of valency. To the graphic symbols of molecules is but a step; the atoms are represented as united together, the valencies indicating the manner of attachment (II.). The directness or indirectness of union of the atoms is here given; no hydrogen atom is in this formula directly attached to another; they are only indirectly united through carbon or oxygen. For brevity, we join up the lines representing the valencies of the various atoms and obtain the customary formula (III.). A great change in significance has, however, at this stage taken place: the valencies have become "bonds"—the idea of force has entered. What that force is remains indeterminate; it is merely something binding atoms together, and the interpretation of the symbols is not quantitative in this respect. The "bonds" do not represent equal forces; it is patent that the bond between hydrogen and carbon in the formula for methyl alcohol represents a different force from that between hydrogen and oxygen. The current symbolism may then be interpreted in two senses; the lines joining the atomic symbols may be taken to represent on one hand merely the union of the atoms to the symbols of which they are attached, or they may represent forces existing between these atoms. Confusion of these two senses sometimes leads to erroneous reasoning.

This dual character of graphic formulæ is noticeable from their earliest employment, and I need make no apology in illustrating it from the work of Crum Brown, whose recent death deprived our Society of its senior past-president. In the formula for glycol quoted above he states (1861) that the dotted lines therein employed represent polar forces. In 1864 he represents ethane thus (IV.),

each valence being written independently. He says: "I may here shortly explain the graphic notation which I employ to express constitutional formulæ.

... An atom is represented by its usual symbol surrounded by a circle with as many lines proceeding from it as the atom contains equivalents. ... When equivalents mutually saturate one another the two lines representing the equivalents are made continuations of one another." Here he has discarded the idea of polar force in his original formulation in favour of the simpler

he writes continuous lines between the symbols, and in 1868 puts the matter thus: "The structural formula of formic acid [V] indicates first, that the four carbon equivalents form one atom, the four oxygen equivalents two atoms, and the two hydrogen equivalents two atoms; secondly, that these equivalents are united in pairs, thus—*co, co, co, ch, ho*; but it does not in any way indicate (and we do not know) what is the *potential* of each of these pairs—that is, how much energy would be required to separate the equivalents from each other. We know that this potential depends upon the structure, and we can to a certain extent trace the nature of this dependence, but as yet we cannot express the potential numerically, and till we can do that we do not fully know the constitution."

On one hand, then, our "bonds" stand for mere units of valency; on the other, they are an imperfect representation of forces. Were the representation of forces more complete, methyl alcohol would appear somewhat as shown in the figure below, the small letters representing numerical values. Even this formula, however, only gives the magnitude and not the real direction of the forces, and is besides static, not kinetic. We naturally shrink from complexity such as this: imagine the formula of sucrose on a similar basis. We must content ourselves with something simpler, and

Methyl Alcohol.

yet the simple valency formula has for long been felt to be inadequate. Apart from the idea of definitely directed valencies which leads to stereochemical formulæ, the idea of representing partial valencies has been constantly in the foreground. We cannot properly split valencies in the old sense, but we can subdivide forces *ad libitum*. If the subdivision is carried too far, however, the formulæ may approach in complexity formulæ with quantitatively measured forces, such as that indicated in the figure.

What the chemist requires in his system of formulation is something, not which he can *measure*, but which he can *count*—counters, in short. Such numerical counters he possesses in valencies, in co-ordination numbers. He may be forced to consider the adoption of counters of different kinds, for the purpose of representing essentially different distributions of force; but these counters, if they are to be of general practical value, must neither be too numerous nor of too great variety. Partial valencies, augmented valencies, diminished valencies, virtual valencies, represented by lines of various sorts, thick, thin, curved, dotted, etc., all tend to complicate formulæ, which lose in obvious-

ness what they gain in definition. The humiliating fact must be admitted that the average man does not succeed in counting quickly and accurately by inspection any larger number of "bonds" than he has fingers on one hand, unless they are appropriately grouped—witness the wrong valencies found, not merely in examination scripts, but even on the printed page. We ought, then, to set strict limits to the splitting of "bonds" and the issue of fractional valency counters. Fortunately, the physicist has provided us with a new counter, the electron, which has the great merit of being a physical reality, and, moreover, of being an undecomposable magnitude, so that there is no temptation and no possibility of dividing it further. This counter enables us practically to halve ordinary valencies, and so offers many advantages. In the original form given by J. J. Thomson, lines in the formulæ are made to represent tubes of force passing from an electron of one atom to the positive core of another, and since in electrically neutral atoms, for each tube of force which passes out of an atom a return tube must come in, directly or indirectly, one valency line on the old scheme is represented by two tubes of force on the new. The new formulation enables us to write, for example, symmetrical formulæ for benzene and for the carboxyl group, if we so desire, thus:

Or, again, we may represent the valency electrons directly in our formulæ, each atom being equipped with its doublet, sextet, or octet. Such formulæ, or modifications of them, are coming extensively into use when multiple bonds are in question, and there is no doubt that with the electron or electronic tube of force as counter we obtain a more adaptable and more flexible formulation of organic compounds than that afforded by the older valency formulæ, although only with some sacrifice of their simple character.

It will be gathered from what I have said that my plea is for the utmost obviousness of our symbols and formulæ. Their content and connotation may be as rich as we please; the symbols themselves should be of elementary simplicity. But, it may be asked, why should we seek to limit the investigator striving for chemical self-expression to four whole valencies for carbon if he wants a dozen partial valencies to facilitate his own thought or to convey his exact meaning? And why should he hesitate to adorn his formulæ with arrows or positive and negative signs of polarity if he feels the necessity? The answer to such questions must be of a practical nature. The investigator for his own use may employ a symbolism as elaborate and as complex as he chooses, but if he wishes to secure the understanding and sympathy of others he must curb any spirit of exuberance. A system of chemical formulation to have general currency must not be too elaborate. Otherwise, although it effects economy of

thought to the expert who devises it, it may demand such a mental strain of the general chemical reader as to defeat a main purpose for which it was planned, namely, the communication of knowledge. I would quote, both with regard to chemical symbolism and to chemical nomenclature, the words used by a character of Henry James concerning literature, "The observer is nothing without his categories, his types and varieties. . . . That's for his own convenience; he has privately a terminology to meet it. . . . But from the moment it's for the convenience of others, the

signs have to be grosser, the shades begin to go. . . . Literature, you see, is for the convenience of others. It requires the most abject concessions." Scientific literature is, above all, for the enlightenment and convenience of others, and scientific specialists must be prepared to make concessions to their weaker or less expert brethren. But whether the symbols we use are simple or complicated, we should always be clear as to their true significance, and be on our guard against their distracting our thoughts from the realities which they partly reveal and partly obscure.

Recent Contributions to Aviation Problems.

By Prof. G. H. BRYAN, F.R.S.

THE attempts which have hitherto been made to explain the continuous sustentation of tropical and other birds without the performance of muscular work have left many doubtful points requiring to be cleared up. Observers have frequently sought to attribute the phenomena to something acting in violation of the principles of elementary mechanics, and have succeeded in establishing this peculiarity, not perhaps in the way that they intended, but by the chaotic way in which such terms as force, momentum, weight, energy, lift, pull, drag, and gravity are confused by them, and occur indiscriminately mixed up in their writings. In a paper on "Meteorology and the Non-Flapping Flight of Tropical Birds," published in the Proceedings of the Cambridge Philosophical Society, xxi. 4, Dr. Gilbert T. Walker has now sought to bring sound scientific principles to bear on the numerous observations in India published by Dr. Hankin. From observations of the temperature of the air at Agra at different altitudes and hours of the day, Dr. Walker finds conditions of instability leading to the formation of strong ascending air-currents, and observations in Egypt and various parts of India indicate conditions of "bumpiness" in the atmosphere caused by ascending currents, covering the periods employed by birds for "soaring."

Dr. Walker finds that the angle of gliding of the most efficient recent aeroplanes is sufficiently low to satisfy the conditions necessary for continuous sustentation in the presence of these currents, and he examines in detail three possible sources of internal work in the atmosphere, namely, ascending currents, variations of horizontal velocity as functions of time and place co-ordinates, and Lord Rayleigh's hypothesis of variation of horizontal wind velocity as a function of the vertical altitude co-ordinate. He also carefully considers the structure of the birds' wings, in comparison with those of the Handley-Page machine, and the effect of the flexibility of the quills on the aerofoil form in ascending and descending glides. Both from theory and from actual observation, it is found that the ascending air-currents in the higher regions of the atmosphere are greater in diameter than lower down, and from actual observation he contradicts Dr. Hankin's statements according to which birds are seen rising in descending currents. It would thus appear from Dr. Walker's observations that, in the region dealt with by Dr. Hankin, the atmosphere possesses sufficient internal energy to satisfy the conditions of "soarability" required by the latter observer. In

regard to the violation of mechanical principles, both hypothetically by birds and actually by writers, we cannot do better than quote Dr. Walker's remark that . . . "it is strangely" (asterisk and footnote with references follow) "necessary to insist that it is as impossible to derive energy from a wind that is constant in time and space as it is from a perfect calm." To theories based on a denial of this principle the late Sir Hiram Maxim used to point out the enormous velocity of the wind due to the earth's rotation and its orbital motion about the sun, and he suggested that if writers believed in these theories, why did not they utilise this energy for the purposes of flight?

The recent records of gliding flight in the daily press afford ample confirmation of Dr. Walker's theories in regard to the quantity of *available* internal energy present in the atmosphere. When we read of aviators remaining for hours in the air under climatic conditions not widely different from those prevailing in Dr. Hankin's and Dr. Walker's investigations, and of 7 horsepower engines making long flights at a cost for fuel of not more than a penny a mile, we have reasonable prospects of realising a system of cheap transport largely superseding the use of wheels bumping over stony roads or iron bars placed end to end.

Apart, however, from the precariousness of the distribution of the necessary internal energy in space and time, a motorless aeroplane is in constant danger of being suddenly brought to rest relative to the air, or, more accurately, losing all headway, at which instant it has a vertical acceleration due to gravity, and the resistance to rotation (pitching, yawing, rolling) becomes technically describable as "a small quantity of the second order," thus approximating to the conditions assumed in the problem of rigid body rotation under no forces.

We are constantly reading of accidents which seem to suggest that they have arisen from this condition of affairs, even in the case of motor-driven machines which are at least equipped with a more adequate means of extricating themselves from this eventuality.

No system of aviation will ever be satisfactory, however, until backed up by a more thorough solution than we now have of the equations of motion of the "perfect aeroplane." Perfect fluids, perfect conductors and dielectrics, perfectly smooth bodies, perfect gases, and so on, are very familiar terms, but the "perfect aeroplane" has not yet figured in literature as such, though various formal representations have been