SCHOOL SCIENCE AND MATHEMATICS

VOL. VIII. No. 6. CHICAGO, JUNE, 1908 WHOLE No. 62

THE EXPERIMENTAL BASIS OF CHEMICAL FORMULAE AND THE TEACHING OF THE ATOMIC-MOLECULAR HYPOTHESIS.

BY HERBERT N. MCCOY,

Kent Chemical Laboratory, University of Chicago.

While an appreciable number of chemists, some of whom are very prominent, are not wholly in sympathy with the atomic hypothesis,¹ there are but few, I think, who would hesitate to acknowledge the practical importance of chemical formulæ. A formula may be interpreted as representing two things: (1) the relative amounts, by weight, of the constituent elements of the substance, each symbol representing a fixed weight of the corresponding element; and (2) the number and kind of atoms in each molecule of the substance. The first interpretation is independent of the second and may be used without reference to the atomic-molecular hypothesis.

In teaching beginners the use of formulæ in either one or both of the above senses it is obviously out of the question to follow, in any faithful detail, the historical development of the subject.² Even an approximate adherence to the historical sequence certainly involves perplexing difficulties for the student. Although there is no question that, in all possible cases, Avogadro's hypothesis is, *at present*, the touchstone on which atomic weights and formulæ are tested, nevertheless this hypothesis was opposed by Dalton, who thought it was contradicted by certain well-known facts. The discovery by Dumas that the vapor densities of sulphur, phosphorus, and mercury were 3, 2, and $\frac{1}{2}$ times those previously assumed on the basis of Avogadro's hypothesis led this famous chemist, in 1832, to abandon the hypothesis. Even Berzelius, the master chemist of his day, who had, up to

¹See, for example, Ostwald, *J. Chem. Soc. London*, 85, 506 (1904).

²Those teachers who, thinking to follow the historical plan, start with the statement that Dalton proposed his hypothesis to explain the facts summarized in the laws of definite and multiple proportions are, apparently, not in accord with the facts; since, as Roscoe and Harden very clearly point out, (*The Origin of Dalton's Atomic Theory*, Macmillan & Co., 1896), Dalton first employed the atomic hypothesis to explain, by the difference in the weights of their atoms, the difference in solubility of various gases.

this time, been one of the few able supporters of Avogadro's hypothesis, now conceded that the hypothesis was not universally valid.³

The open disagreement among chemists as to which of two or more "combining weights" of an element was to be selected as its atomic weight led Wollaston to propose, in 1814, the Doctrine of Equivalents. His idea was to replace atomic weights, based upon hypotheses, by equivalent weights, based as he thought, upon experimentally determined facts. Although Wollaston's idea was welcomed and ardently championed by many, the facts epitomized by the Law of Multiple Proportions show that the assignment to an element of a definite equivalent weight was just as much an arbitrary process as was the fixing of its atomic weight in any manner previously employed. The history of chemistry shows that Wollaston's lamentable fallacy proved an Old Man of the Sea on the back of the science, that was not shaken off for more than forty years.

The remarkable clearness with which Cannizzaro, in 1858, showed⁴ that Avogadro's hypothesis was not in conflict with any known fact, and that by the acceptance of this hypothesis order could be brought out of what might well be called chaos, led, as is well known, to the establishment of modern atomic weights and formulæ.

While the historical plan of presenting a subject is ordinarily the preferable one, it is, in this case, in my opinion, impracticable for beginners. If then one decides to forego the historical treatment, he may be free to teach the significance and use of formulæ without, at first, any reference to the atomic-molecular hypothesis, and this is, I think, a distinct advantage from the standpoint of simplicity. Later in the course, after the student has become quite familiar with formulæ and equations and a greater range of chemical facts, it will be an easy matter to introduce the atomic-molecular hypothesis.

The following pages contain an outline of the topics under discussion as I have presented them to my classes during the past school year. The outline consists of two parts: the first deals with the derivation of chemical formulæ without reference to any hypothesis; the second with the interpretation of the facts in terms of the hypotheses of Dalton and Avogadro. The argu-

³See Ladenburg, *History of Chemistry*, Chaps. IV and VI.

⁴Ostwald's *Klassiker der Exakten Wissenschaften*, No. 30.

ments as here presented may be considered merely a syllabus of the subject: in many cases illustrative explanations, in greater or less detail, must take the place of the brief general statements. The pupil should be able to appreciate the arguments regarding formulæ after the following subjects have been considered: (1) The Conservation of Matter; (2) The limited decomposability of matter and the Doctrine of Elements; (3) The Law of Definite Composition; (4) The Laws of Gases.

1. The Experimental Basis of Chemical Formulæ.

One may weigh a known volume, measured at definite temperature and pressure, of any gaseous substance and then calculate, by the laws of gases, the weight of one liter of the gas at 0° C. and 760 mm. Many pure liquid or solid substances are volatile at temperatures somewhat above the ordinary. The vapors of such substances may be treated as gases and, in each case, the weight of one liter may be calculated for standard conditions.

Every pure substance has a definite composition; this composition is found, in any case, as the result of a specific quantitative experiment. This result may be expressed in terms of the percentage of each constituent element. Table 1 shows the weight of one liter, under standard conditions, and the percentage composition of 32 substances, which are either gaseous at ordinary temperatures or are easily volatile. The values for the densities of gases were, as a rule, taken from Landolt, Börnstein, and Meyerhoffer Tables, 1905, p. 222. Most of the vapor densities of liquids and solids were taken from an extensive table in Lothar Meyer's *Die Modernen Theorien der Chemie*. All other values were taken from original sources. It has been my aim to give as weights of 1 l. of gas or vapor, in both Tables 1 and 4, only actual, experimentally determined, values. The abbreviation of the name of the observer is appended to each value. These abbreviations are as follows:

B., Berthelot; Ds., Dumas; D. P., Dumas and Peligot; D. T., Deville and Troost; D. M., Dacomo and V. Meyer; E. L., Emmerling and Lengyel; G., Garzarolli and Schacherl; I., Izarn; Jq., Jaquelin; K., Kolbe; Lo. Löwig; L., Leduc; M. L., Mond, Langer and Quincke; Mt., Mitcherlich; P., Pebal; Ra., Rayleigh; Rg., Regnault; Rc., Roscoe; R. S., Ramsay and Steele; S., Saus-

sure; Sa., Salet; Th., Thenard; Tm., Thomson; Ti., Tilden; V. M., Victor Meyer; W. D., Wöhler and Deville.

Table 1.

	Weight of 1 Liter	Percentage of Each Constituent				
		Oxygen	Hydrogen	Carbon	Nitrogen	Chlorine
Oxygen	1.4296 Ra.	100.00				
Water	0.8063 Rg.	88.81	11.19			
Carbon Monoxide...	1.2503 L.	57.14		42.86		
Carbon Dioxide....	1.9766 Ra.	72.73		27.27		
Nitrous Oxide	1.978 L.	36.35			63.65	
Nitric Oxide	1.341 D.M.	53.31			46.69	
Nitrosyl Chloride....	2.987 Ti.	24.44			21.40	54.16
Hypochlorous Oxide	3.889 G.	18.41				81.59
Chlorine Dioxide....	3.013 P.	47.43				52.57
Phosgene	4.532 E.L.	16.17		12.13		71.70
Methyl Alcohol.....	1.440 R.S.	49.95	12.58	37.47		
Ethyl Alcohol	2.086 G.L.	34.74	13.13	52.13		
Methyl Ether.....	2.091 D.P.	34.74	13.13	52.13		
Ethyl Ether.....	3.340 R.S.	21.60	13.60	64.80		
Hydrogen	0.0900 Ra.		100.00			
Hydrogen Chloride..	1.642 L.		2.76			97.24
Prussic Acid.....	1.226 G.L.		3.73	44.42	51.85	
Chloroform.....	5.430 Ds.		0.84	10.05		89.11
Ammonia	0.7722 L.		17.76		82.24	
Methane.....	0.7212 Tm.		25.15	74.85		
Acetylene	1.190 B.		7.75	92.25		
Ethylene	1.274 S.		14.38	85.62		
Ethane	1.390 K.		20.13	79.87		
Propylene	1.937 B.		14.39	85.61		
Benzene.....	3.557 R.S.		7.75	92.25		
Methyl Chloride....	2.238 D.P.		5.99	23.77		70.24
Ethyl Chloride.....	2.870 Th.		7.81	37.22		54.97
Methyl Amine.....	1.396 I.		16.23	38.65		45.12
Nitrogen	1.2506 L.				100.00	
Cyanogen	2.335 G.L.			46.13	53.87	
Cyanogen Chloride..	2.754 Sa.			19.52	22.79	57.69
Chlorine.....	3.221 L.					100.00

The values given in Table I represent direct experimental results. Thus, for example, in the case of water, as a result of four determinations at about 100° and 350 mm., Regnault⁵ found the weight of one liter of water vapor to be 0.8063 g. for 0° C. and 760 mm.; and Morley⁶ found the composition to be 11.19 per cent of hydrogen and 88.81 per cent of oxygen.

The weight of hydrogen contained in 1 l. of water vapor, at standard conditions, is, of course, $0.1119 \times 0.8063 \text{ g} = 0.090 \text{ g}$. The weight of any other element in one liter of any other vapor, at standard conditions, may be found in a similar manner. These

⁵Ann. Chim. Phys., [3], 15, 145 (1845).

⁶Smithsonian Reports, 1895.

derived data, which are given in Table 2, represent experimentally determined facts just as truly as do those of Table 1.

From an inspection of the figures in Table 2, the student will have no trouble in seeing two important relationships. It will appear (1) that for any one element there is an approximate *minimum weight* per liter; and (2) that all other weights per

Table 2.

	Weight per Liter of Each Constituent				
	Oxygen	Hydrogen	Carbon	Nitrogen	Chlorine
Oxygen.....	1.4296				
Water.....	.716	.090			
Carbon Monoxide.....	.715		.536		
Carbon Dioxide.....	1.437		.540		
Nitrous Oxide.....	.719			1.259	
Nitric Oxide.....	.715			.626	
Nitrosyl Chloride.....	.730			.639	1.618
Hypochlorous Oxide.....	.717				3.172
Chlorine Dioxide.....	1.429				1.584
Phosgene.....	.733		.550		3.249
Methyl Alcohol.....	.720	.180	.539		
Ethyl Alcohol.....	.725	.273	1.089		
Methyl Ether.....	.726	.274	1.091		
Ethyl Ether.....	.722	.454	2.164		
Hydrogen.....		.090			
Hydrogen Chloride.....		.045			1.597
Prussic Acid.....		.046	.545	.635	
Chloroform.....		.046	.545		4.839
Ammonia.....		.137		.635	
Methane.....		.181	.540		
Acetylene.....		.092	1.098		
Ethylene.....		.183	1.091		
Ethane.....		.280	1.110		
Propylene.....		.279	1.658		
Benzene.....		.276	3.281		
Methyl Chloride.....		.134	.532		1.572
Ethyl Chloride.....		.224	1.068		1.578
Methyl Amine.....		.226	.540	1.630	
Nitrogen.....				1.2506	
Cyanogen.....			1.077	1.258	
Cyanogen Chloride.....			.537	.628	1.589
Chlorine.....					3.221

liter of that element are approximate *multiples of the minimum weight*. These relationships may be stated as laws and called the Law of Minimum Weights and the Law of Multiple Weights respectively: they are real natural laws.

For the five elements comprised in Table 2, the minimum weights per liter are approximately as follows:

Hydrogen	.045
Oxygen	.715
Nitrogen	.628
Carbon	.536
Chlorine	1.583

It is obvious that the laws of minimum and multiple weights, which have been deduced for the volume one liter, must hold equally well for any other fixed volume. By choosing a certain larger volume the minimum weight of hydrogen, for that volume, may be made approximately 1 gram. All of the other minimum weights will then be greater than 1 gram, and several of them will be approximately whole numbers. In a volume of 22.4 l. the minimum weights, in grams, are approximately as follows:

Hydrogen	1.0
Oxygen	16.0
Nitrogen	14.0
Carbon	12.0
Chlorine	35.5

It follows also that the weight of any element in 22.4 l. of a gas or vapor, under standard conditions, is approximately an even multiple of the minimum weight of that element contained in 22.4 l.

It is quite clear that the numerical relationships just discussed are only approximate. For any one element, say oxygen, we may state the law of multiple weights in either one of the two following ways: (1) The weight of oxygen in *exactly* 22.4 l. of any gas or vapor, under standard conditions, is either *approximately* 16 g. or *approximately* a multiple of 16 g. by a small whole number; or, (2) The weight of oxygen in *approximately* 22.4 l. of any gas or vapor, under standard conditions, is either *exactly* 16 g. or an *exact* multiple of 16 g. by a small whole number. The last column of Table 3 shows the exact volume (nearest 22.4 l.) in which the weight of oxygen, for any substance, is either exactly 16 g. or an exact multiple of 16 g. by a small whole number. The weights of hydrogen, nitrogen, carbon and chlorine which combine with exactly 16 g. or some exact multiple of 16 g. of oxygen, as given in Table 3, are also given. It will be seen that the weight of carbon, for example, is, in any case, either 12.00 g. or an exact multiple of 12.00 g. by a small integer. The weight of each other element combined, in any case, with the weight of oxygen indicated in that case in Table 3 is an exact multiple by unity or some other small integer of a characteristic weight which is approximately the minimum weight, in 22.4 l., for that element. These weights for the other elements under consideration are as follows: hydrogen, 1.008 g.; chlorine, 35.45 g.; nitrogen, 14.01 g.

In the case of a compound which does not contain oxygen, if that volume, nearest 22.4 l., is found in which the weight of any one of its elements is an exact multiple of the weight just given for that element, then, for that compound, in the volume so fixed, the weight of every other element is also an exact multiple of its characteristic weight. In other words Table 3 shows that the composition, by weight, of any compound can be exactly expressed in terms of small integral multiples of certain characteristic numbers, one for each element. This is one form of statement of the Law of Reciprocal Proportions.

Table 3.

	Oxygen	Hydrogen	Carbon	Nitrogen	Chlorine	Wght.	Volumes
Oxygen.....	2×16.00					32.00	22.38
Water.....	1×16.00	2×1.008				18.02	22.34
Carbon Monoxide...	1×16.00		1×12.00			28.00	22.40
Carbon Dioxide....	2×16.00		1×12.00			44.00	22.25
Nitrous Oxide.....	1×16.00			2×14.01		44.02	22.25
Nitric Oxide.....	1×16.00			1×14.01		30.01	22.38
Nitrosyl Chloride...	1×16.00			1×14.01	1×35.45	65.46	21.92
Hypochlorous Oxide.	1×16.00				2×35.45	86.90	22.35
Chlorine Dioxide....	2×16.00				1×35.45	67.45	22.39
Phosgene.....	1×16.00		1×12.00		2×35.45	98.90	21.82
Methyl Alcohol.....	1×16.00	4×1.008	1×12.00			32.03	22.23
Ethyl Alcohol.....	1×16.00	6×1.008	2×12.00			46.05	22.07
Methyl Ether.....	1×16.00	6×1.008	2×12.00			46.05	22.02
Ethyl Ether.....	1×16.00	10×1.008	4×12.00			74.08	22.18
Hydrogen.....		2×1.008				2.02	22.44
Hydrogen Chloride..		2×1.008			1×35.45	36.46	22.21
Prussic Acid.....		1×1.008	1×12.00	1×14.01		27.02	22.04
Chloroform.....		1×1.008	1×12.00		3×35.45	119.36	21.98
Ammonia.....		3×1.008		1×14.01		17.03	22.05
Methane.....		4×1.008	1×12.00			16.03	22.23
Acetylene.....		2×1.008	2×12.00			26.02	21.87
Ethylene.....		4×1.008	2×12.00			28.03	22.00
Ethane.....		6×1.008	2×12.00			30.05	21.62
Propylene.....		6×1.008	3×12.00			42.05	21.70
Benzene.....		6×1.008	6×12.00			78.05	21.96
Methyl Chloride....		3×1.008	1×12.00		1×35.45	50.47	22.55
Ethyl Chloride.....		5×1.008	2×12.00		1×35.45	64.49	22.47
Methyl Amine.....		5×1.008	1×12.00	1×14.01		31.05	22.24
Nitrogen.....				2×14.01		28.02	22.40
Cyanogen.....			2×12.00	2×14.01		52.02	22.28
Cyanogen Chloride..			1×12.00	1×14.01	1×35.45	61.46	22.32
Chlorine.....					2×35.45	70.90	22.12

Suppose we represent by H 1.008 g. of hydrogen and by O 16.00 g. of oxygen; then, since 2×1.008 g. of hydrogen combine with 16.00 g. of oxygen, 2 H together with O, which we may write H₂O, will represent the composition of water and, more-

over, that quantity of water which as vapor under standard conditions would occupy approximately 22.4 l. H and O are the *symbols* for hydrogen and oxygen respectively and H_2O is the *formula* for water. Similarly N represents 14.01 g. of nitrogen; C. 12.00 g. of carbon; and Cl. 35.45 g. of chlorine. The composition of any compound of these five elements may be exactly expressed by a formula constructed from the appropriate symbols. Thus C_2H_5O represents the composition of alcohol and shows that in approximately 22.4 l. of the vapor, under standard conditions, there are contained 2×12.00 g. of carbon united with 6×1.008 g. of hydrogen and 16.00 g. of oxygen. The formulæ of the elementary gases studied are H_2 , O_2 , N_2 and Cl_2 , since each of these gases contains in approximately 22.4 l. double the weight represented by the symbol of the corresponding element.

The argument here presented is essentially an elaboration of that of Cannizzaro, made fifty years ago, to which reference has already been made. Table 4 is a reproduction, abbreviated in length only, of Cannizzaro's principal table, which included values for 26 additional substances.

Table 4.

NAME OF THE SUBSTANCE	Weight of one volume or molecular weight referred to the weight of a half hydrogen molecule = 1	Weight of the constituents of one volume or of one molecule, all referred to the weight of a half hydrogen molecule = 1
Hydrogen	2	2 Hydrogen
Oxygen	32	32 Oxygen
Hydrochloric Acid.	36.5	35.5 Chlorine, 1 Hydrogen
Water	18	16 Oxygen, 2 Hydrogen
Ammonia	17	14 Nitrogen, 3 Hydrogen
Alcohol.	46	6 Hydr'g'n, 16 Oxyg'n, 24 Carb'n

It is evident that Cannizzaro's figures for the "weight of one volume" are rounded, *idealized* values. In my own tables *experimentally observed* gas densities have been used in order to make the treatment more concrete and to show as clearly and directly as possible the experimental basis of chemical formulæ.*

The scheme which I have followed in the cases of five elements and their compounds may be extended so as to embrace a large

*Prof. Alexander Smith has called my attention to the chapter on symbols, formulæ and equations in Linebarger's Elementary Chemistry, (Rand, McNally & Co., Chicago, 1904) where the plan of treatment is somewhat similar to that which I am advocating. The author gives, in a single table, the weights of 1 liter of 12 gases or vapors and the weights of hydrogen, carbon, oxygen and nitrogen in one liter of each substance. The weights per liter, in most cases, are not the *real, observed* values, but, like Cannizzaro's, are those which evidently have been calculated from the formulæ, on the assumption that gas densities are *strictly proportional to formulæ weights*.

proportion of the commoner elements. The following table, Table 5, gives the name of one volatile compound of each common element in which the minimum weight of that element per liter of vapor is contained. The minimum weights in 22.4 l. given in column 2, are *approximately* the weights represented by the corresponding symbols. The *exact* weight represented by the symbol, in any case, is found as the result of a very accurate determination of the composition of some compound of the element with an element of known symbol weight.

In the cases of those elements which form volatile compounds, the symbol weights, as found in the manner discussed in the preceding pages, multiplied by the respective specific heats of the solid elements give approximately the same product. This, law, discovered by Dulong and Petit in 1819, may be applied to find the approximate symbol weights of those elements which do not readily form volatile compounds: the exact values represented by the symbols are found, as in other cases, by very accurate quantitative analyses or syntheses.

In the case of any volatile substance, the formula is written so as to represent the number of symbol weights of each constituent in approximately 22.4 l. of the vapor, under standard conditions. If we now indicate in terms of formulæ, so constructed, the relative amounts of the reacting substances we have *equations*, such as the following: $2\text{H}_2 + \text{O}_2 \longrightarrow \text{H}_2\text{O}$.

It is an experimentally established fact that, at a fixed temperature and pressure, 2 volumes of hydrogen unite with one volume of oxygen to form 2 volumes of steam. The equation indicates that 2×22.4 l. of hydrogen unite with 22.4 l. of oxygen to form 2×22.4 l. of water vapor, approximately, for standard conditions. In all cases, *coefficients of formulæ*, in equations for substances wholly in the gaseous state, *show the relative reacting volumes*.

II. The Atomic-Molecular Hypothesis.

Perhaps the best mental picture of the nature of matter is afforded by the *Atomic-Molecular Hypothesis*, according to which all matter is conceived of as composed of minute indivisible particles, called atoms. This ancient Greek hypothesis was reintroduced into chemistry by Dalton in 1803. Dalton supposed the atoms of a simple substance to be all alike in size, weight, and all other properties. Atoms of like or different sorts were

supposed by Dalton to combine or unite in simple ratios, by numbers; e. g., 1:1; 1:2; 1:3; 2:3; etc.; the groups of atoms so formed are now called molecules. For example, according to Dalton's hypothesis, one molecule of any definite hydrogen com-

Table 5.

VOLATILE COMPOUNDS OF VARIOUS ELEMENTS	Density Air = 1	Weight of El. in 22.4 l.	Symbol and Symbol Weight
Antimony Trichloride.....	7.8 Mt.	119.5	Sb = 120.2
Arsenic Trichloride.....	6.30 Ds.	75.4	As = 75.0
Bismuth Trichloride.....	11.35 Jq.	217.	Bi = 208.5
Boron Trichloride.....	4.02 W. D.	10.9	B = 11.0
Hydrogen Bromide.....	2.71 Lo.	78.	Br = 79.96
Cadmium.....	3.94 D. T.	114.	Cd = 112.4
Chromium Oxychloride....	5.69 Ds.	55.	Cr = 52.1
Methyl Fluoride.....	1.186 Ds. P.	19.2	F = 19.0
Hydrogen Iodide.....	4.443 G. L.	127.7	I = 127.97
Iron Carbonyl.....	6.45 M. L.	53.2	Fe = 55.9
Lead Chloride.....	9.6 Rc.	207.2	Pb = 206.9
Mercury.....	6.98 Ds.	202.2	Hg = 200.0
Nickel Carbonyl.....	6.01 M. L.	59.7	Ni = 58.7
Phosphorus Trichloride....	4.88 Ds.	31.9	P = 31.0
Silicon Tetrachloride.....	5.94 Ds.	28.7	Si = 28.4
Zinc Chloride.....	4.57 V. M.	63.5	Zn = 65.4

pound will contain 1, 2, 3, or some small integral number of hydrogen atoms; similarly one molecule of a definite oxygen compound will contain some small integral number of oxygen atoms. If, now, we suppose these two compounds to interact, so that water is formed by the union of the hydrogen of the first with the oxygen of the second; and if, according to the atomic hypothesis, the atoms of hydrogen and oxygen unite in simple ratios; then, as a necessary consequence, the numbers of molecules of the two reacting substances must be in the ratio of small whole numbers. Similarly, for all substances, according to Dalton's hypothesis, molecules must react with one another, in numbers which, in any given case, may be represented by a simple ratio.

When gases react, in any particular case, at a fixed temperature and pressure, the volumes of the initial substances, and also of the products if gaseous, are in simple ratios. From a consideration of the facts represented by this *Law of Volumes*, first stated by Gay Lussac in 1808, and of the hypothesis of Dalton, we may reach a very important conclusion, namely: That the numbers of molecules in equal volumes of all gases at the same temperature and pressure are either *equal* or in a *simple ratio*.

In 1811 Avogadro advocated the hypothesis that equal volumes of all gases or vapors at the same temperature and pressure contain equal numbers of molecules. Since this supposition represents one of the several possibilities, according to the Dalton Hypothesis and the Gay Lussac Law, it is therefore in complete accord with the facts so far discussed as well as with the views of Dalton. Modern investigation has shown, however, that Gay Lussac's Law is not mathematically exact; but is only a close approximation, the deviations amounting usually to less than one per cent. The strict modern statement of Avogadro's hypothesis is that equal numbers of molecules are contained in approximately equal volumes of gases or vapors, at the same temperature and pressure.

Each molecule of any definite substance contains, according to Dalton's hypothesis, a definite small number of atoms of one or more sorts; but each molecule cannot contain less than one atom of any given element; consequently the minimum number of atoms of that element per liter is the same as the number of molecules per liter, which is the same for all gases. Therefore a gas in which each molecule contains but one atom of a given element, will contain the minimum possible weight per liter of that element. This, then, is the theoretical explanation of the Law of Minimum Weights. On the other hand, in a gas which contains more than the minimum weight of a given element per liter, each molecule must contain 2, 3, 4 or some small whole number of atoms of the element and therefore one liter of the gas must contain 2, 3, 4 or some small integral multiple of the minimum weight per liter of that element; and this is the explanation of the Law of Multiple Weights.

According to the arguments just discussed, a gas which contains the minimum weight per liter of any element must have but one atom of that element in each molecule. Equal volumes of such gases contain the same number of atoms of the element of minimum weight per liter, since they contain the same number of molecules. The minimum weights per liter are, therefore, the relative weights of equal numbers of atoms. The weights of equal volumes of various gases or vapors are proportional to the weights of their respective molecules.

But, as we do not know, very exactly, the absolute weight of any atom or molecule, a value may be assigned arbitrarily as the weight of any sort of atom; the weight of every other sort of

atom or molecule may then be expressed on the same basis. The values so obtained are called atomic or molecular weights. Dalton's atomic and molecular weights were based upon the atomic weight of hydrogen chosen as unity. Berzelius chose at one time oxygen with an atomic weight of 100 as the basis of calculation. Most chemists of to-day prefer values based on oxygen with an atomic weight of 16; but obviously the choice of a standard is an arbitrary matter.

The following example will serve to show how atomic and molecular weights are found from the experimental data. Water contains the minimum weight of oxygen per liter (Table 2); therefore each molecule of water contains but one atom of oxygen. If, now, we take 16 as the weight of one atom of oxygen, the weight of a molecule of water is 18.016; since 16.00 g. of oxygen are contained in 18.016 g. of water. The weight of hydrogen combined with 16.00 g. of oxygen is 2.016 g. But water contains twice the minimum weight of hydrogen per liter (Table 2) and therefore two atoms of hydrogen in each molecule or to each atom of oxygen. If 16.00 is taken as the atomic weight of oxygen, then $\frac{1}{2}$ of $2.016 = 1.008$ is the atomic weight of hydrogen. The atomic weights of oxygen and hydrogen are thus identical with their respective symbol weights. The same relationship holds for all other elements considered.

In Table 3, the factor of any symbol-weight represents the number of atoms of the indicated element contained in one molecule of the substance. The formula-weight, in grams, Table 3, is numerically equal to the molecular weight which is the sum of the weights of the atoms in the molecule, on the basis of 16 as the atomic weight of oxygen. From the standpoint of the atomic-molecular hypothesis, the formula of water, H_2O , represents two atoms of hydrogen combined with one atom of oxygen to form a molecule.

In the foregoing paragraphs I have tried to present in concise form a collection of facts and arguments intended to show that chemical formulae and equations have a direct experimental basis, independent of any hypothesis regarding the structure of matter; and that the symbol and formula weights may be found in a very simple way without reference to the atomic-molecular hypothesis. I have also endeavored to point out how, according to this scheme, the hypotheses of Dalton and Avogadro are readily applied in logical explanation of the facts epitomized by chemical formulae.