purified substance itself exhibited little or no immunological reactivity. On the basis of these and other tests, Avery and his collaborators concluded that the active fraction consisted principally, if not solely, of a highly polymerized form of desoxyribonucleic acid.

Avery thus showed that, in one instance at least, DNA was the active causative factor in an inherited variation in bacterial cells. The experiments showed that the preparations most active in bringing about transformation were those purest and most protein-free, thereby effectively casting doubt on the widespread and commonly accepted belief that proteins were the mediators of biological specificity and cellular inheritance. It was to a great extent through this work that the stage was set for the rapidly ensuing elaboration of the structure, function, and importance of DNA. Avery himself speculated about the mechanism of specificity determination and pointed out that "There is as yet relatively little known of the possible effect that subtle differences in molecular configuration may exert on the biological specificity of these substances,"[3] a situation that was well on the way to being remedied within ten years with the development of the Watson-Crick model for the DNA molecule.

NOTES

1. *J. Exp. Med.*, **26** (1917), 477–493; *Proc. Soc. Exp. Biol. Med.*, **14** (1917), 126–127.
2. *J. Exp. Med.*, **79** (1944), 137–158.
3. *Ibid.*, p. 153.

BIBLIOGRAPHY

I. Original Works. Avery's major early work, on the immunological specificity of the pneumococcus involved in lobar pneumonia, is to be found in his two 1917 papers with A. Dochez, "The Elaboration of Specific Soluble Substance by Pneumococcus During Growth," in *Journal of Experimental Medicine*, **26** (1917), 477–493, also published in the *Transactions of the Association of American Physicians*, **32** (1917), 281–298, and "Soluble Substance of Pneumococcus Origin in the Blood and Urine During Lobar Pneumonia," in *Proceedings of the Society for Experimental Biology and Medicine*, **14** (1917), 126–127. The majority of his work on the chemical nature of the soluble specific substance appeared in a series of papers with M. Heidelberger: "Soluble Specific Substance of Pneumococcus," in *Journal of Experimental Medicine*, **38** (1923), 73–79; "The Specific Soluble Substance of Pneumococcus," in *Proceedings of the Society for Experimental Biology and Medicine*, **20** (1923), 434–435; and "The Soluble Specific Substance of Pneumococcus," in *Journal of Experimental Medicine*, **40** (1924), 301–316. The one paper for which Avery is best known reported his work with MacLeod and McCarty, "Studies on the Chemical Nature of the Substance Inducing Transformation of Pneumococcal Types. Induction of Transformation by a Desoxyribonucleic Acid Fraction Isolated from Pneumococcus Type III," in *Journal of Experimental Medicine*, **79** (1944), 137–158.

II. Secondary Literature. Complete bibliographies of Avery's work can be found appended to two major biographical sketches written by former colleagues: R. J. Dubos, in *Biographical Memoirs of Fellows of the Royal Society*, **2** (1956), 35–48; and A. R. Dochez, in *National Academy of Sciences, Biographical Memoirs*, **32** (1958), 32–49.

Alan S. Kay

AVICENNA. See **Ibn Sīnā.**

AVOGADRO, AMEDEO (*b.* Turin, Italy, 9 August 1776; *d.* Turin, 9 July 1856), *physics, chemistry.*

He was the son of Count Filippo Avogadro and Anna Maria Vercellone. His father was a distinguished lawyer and higher civil servant who had become a senator of Piedmont in 1768 and had been appointed advocate general to the senate of Vittorio Amedeo III in 1777. His subsequent important administrative work led to his being chosen under the French rule of 1799 to reorganize the senate, of which he was made president. Amedeo Avogadro received his first education at home but went to the grammar school in Turin for his secondary education. Coming from a family well established as ecclesiastical lawyers (the name *Avogadro* itself probably being a corruption of *Advocarii*), Avogadro was guided toward a legal career and in 1792 he became a bachelor of jurisprudence. In 1796 he gained his doctorate in ecclesiastical law and began to practice law. In 1801 he was appointed secretary to the prefecture of the department of Eridano. Avogadro also showed interest in natural philosophy, and in 1800 he began to study privately mathematics and physics. Probably he was particularly impressed by the recent discoveries of his compatriot Alessandro Volta, since the first scientific research undertaken by Avogadro (jointly with his brother Felice) was on electricity in 1803.

In 1806 he was appointed demonstrator at the college attached to the Academy of Turin, and on 7 October 1809 he became professor of natural philosophy at the College of Vercelli. In 1820 when the first chair of mathematical physics (*fisica sublime*) in Italy was established at Turin with a salary of 600 lire, Avogadro was appointed. The political changes of 1821 led to the suppression of this chair, which Avogadro lost in July 1822. In 1823 he was given the purely honorary title of professor emeritus by way

AVOGADRO

of compensation. When the chair was reestablished in 1832 it was first given to Cauchy. At the end of 1833 Cauchy went to Prague, and on 28 November 1834 Avogadro was reappointed. He held this position until his retirement in 1850.

In 1787 Avogadro succeeded to his father's title. He married Felicita Mazzé and they had six children. Avogadro was described in the *Gazzetta Piemontese* after his death as "religious but not a bigot."

Avogadro led an industrious life. His modesty was one of the factors contributing to his comparative obscurity, particularly outside Italy. Unlike his great contemporaries Gay-Lussac and Davy, he worked in isolation. Only toward the end of his life do we find letters exchanged with leading men of science in other countries. Avogadro's isolation cannot be attributed to language difficulties. He wrote good French, understood English and German, and kept abreast of all developments in physics and chemistry.

On 5 July 1804 Avogadro was elected a corresponding member of the Academy of Sciences of Turin, and on 21 November 1819 he became a full member of the Academy. His name is conspicuously absent from the foreign membership of the Paris Academy of Sciences and the Royal Society of London. Avogadro was a member of a government commission on statistics and served as president of a commission on weights and measures. In this latter capacity he was largely responsible for the introduction of the metric system in Piedmont. After 1848 Avogadro served on a commission on public instruction.

Avogadro is known principally for Avogadro's hypothesis, which provided a much-needed key to the problems of nineteenth-century chemistry by distinguishing between atoms and molecules. Dalton had considered the possibility that equal volumes of all gases might contain the same number of atoms but had rejected it. The source of Avogadro's inspiration was not however Dalton but Gay-Lussac, whose law of combining volumes of gases was published in 1809. In Avogadro's classic memoir of 1811 he wrote:

> M. Gay-Lussac has shown in an interesting memoir . . . that gases always unite in a very simple proportion by volume, and that when the result of the union is a gas, its volume also is very simply related to those of its components. But the quantitative proportions of substances in compounds seem only to depend on the relative number of molecules which combine, and on the number of composite molecules which result. It must then be admitted that very simple relations also exist between the volumes of gaseous substances and the numbers of simple or compound molecules which form them. The first hypothesis to present itself in this connection, and apparently even the only admissible one, is the supposition that *the number of integral molecules in any gas is always the same for equal volumes, or always proportional to the volumes*. . . . The hypothesis we have just proposed is based on that simplicity of relation between the volumes of gases on combination, which would appear to be otherwise inexplicable.[1]

Avogadro, therefore, modestly presented his hypothesis as no more than an extension of Gay-Lussac's law.

From Avogadro's hypothesis there immediately follows the inference that the relative weights of the molecules of any two gases are the same as the ratios of the densities of these gases under the same conditions of temperature and pressure. Molecular weights could thus be determined directly. The hypothesis also enabled the chemist to deduce atomic weights without recourse to Dalton's arbitrary rule of simplicity. The molecular weight of water would be calculated in the following way:

$$\frac{\text{Weight of molecule of oxygen}}{\text{Weight of molecule of hydrogen}}$$
$$= \frac{\text{Density of oxygen}}{\text{Density of hydrogen}} = \frac{1.10359}{0.07321} = \frac{15.074}{1}.$$

As water is produced by the combination of two volumes of hydrogen with one of oxygen, this would give for the weight of two molecules of water vapor: $15 + 2 = 17$. The weight of one molecule would therefore be 8.5 (or, more accurately, 8.537). This agreed well with the known density of water vapor referred to the hydrogen standard. It should be noted that Avogadro's molecular weights are values based on the comparison with the weight of a molecule of hydrogen rather than an atom of hydrogen. The molecular weights given in Avogadro's paper of 1811 are therefore half the modern values. However expressed, they were a vast improvement on Dalton's values.

The superiority of Avogadro's method of deriving the molecular weights of compounds over that of Dalton is seen not only with water but with many other compounds. Where the values given by Avogadro were of the same order as those given by Dalton, the Italian pointed out that this resulted from the canceling out of errors. Avogadro was, however, completely fair in his criticism of Dalton, and at the end of his memoir he modestly concluded that his hypothesis was "at bottom merely Dalton's system furnished with a new means of precision from the connection we have found between it and the general fact established by Gay-Lussac."

It is necessary to comment on Avogadro's use of the term *molecule.* Although it has been suggested that he used the term inconsistently, a close examination of his memoir enables us to distinguish four uses of the term: *molécule* ("molecule"), a general term denoting either what today would be called an atom or a molecule; *molécule intégrante* ("integral molecule"), corresponding to the present-day usage of molecule, particularly in relation to compounds; *molécule constituante* ("constituent molecule"), denoting a molecule of an element; and *molécule élémentaire* ("elementary molecule"), denoting an atom of an element. Although Avogadro deserves credit for his application of these expressions, he did not invent them. The terms *partie intégrante, molécule primitive intégrante,* and *partie constituante* are to be found in Macquer's *Dictionnaire de chimie* of 1766 (article on "Agrégation"); and the terms *integrant, constituent,* and *elementary* molecules are to be found in Fourcroy's textbook of 1800.

Avogadro had a solution to the problem that arose when the hypothesis of equal volumes was applied to compound substances. Gay-Lussac had shown that (above 100°C.) the volume of water vapor was twice the volume of oxygen used to form it. This was possible only if the molecule of oxygen was divided between the molecules of hydrogen. Dalton had seen this difficulty and, as it was to him inconceivable that the particles of oxygen could be subdivided, he had rejected the basic hypothesis that Avogadro was now defending. Avogadro overcame the difficulty by postulating compound molecules. This is the second and most important part of Avogadro's hypothesis. It may be regarded as his second hypothesis; and, unlike the first, it seems completely original. Avogadro wrote: "We suppose . . . that the constituent molecules of any simple gas whatever . . . are not formed of a solitary elementary molecule, but are made up of a certain number of these molecules united by attraction to form a single one." Compound molecules of gases must therefore be composed of two or more atoms. Avogadro implies that there are always an even number of atoms in the molecule of a gas. For nitrogen, oxygen, and hydrogen it is two, "but it is possible that in other cases, the division might be into four, eight, etc." Avogadro is not at his clearest in this part of the memoir, but clarity is achieved when he gives an example: "Thus, for example, the integral molecule of water will be composed of a half-molecule of oxygen with one molecule, or, what is the same thing, two half-molecules, of hydrogen."

Avogadro's reasoning about the divisibility of the integrant molecule raises the question of atomicity. Gases for Avogadro were usually diatomic, but certain substances could be tetratomic in the vapor state, as indeed phosphorus is. In later memoirs he allowed for the possibility of monatomic molecules, as, for example, in gold. In his work there is implicit the idea of equivalence, e.g., that one atom of oxygen is equivalent to two atoms of hydrogen, which in turn is equivalent to two atoms of chlorine. The concept of valency, was, however, not developed until the time of Frankland (1852).

In a second memoir, which he sent in January 1814 for publication in Lamétherie's *Journal de physique,* Avogadro developed his earlier ideas. He began by pointing out that no alternative explanation had been offered to the one published by him three years previously to account for Gay-Lussac's law of combining volumes of gases. He suggested that his hypothesis could be used to correct the theory of definite proportions, which he now saw as "the basis of all modern chemistry and the source of its future progress." It was therefore important "to establish by facts, or in default, by probable conjectures, the densities which the gases of different substances would have at a common pressure and temperature." The recent experimental work of Gay-Lussac, Davy, Berzelius, and others now gave Avogadro scope to apply his principle to a greater number of substances. In 1811 Avogadro had been able to give the modern formulas (in words) for water vapor, nitric oxide, nitrous oxide, ammonia, carbon monoxide, and hydrogen chloride. In 1814 he was able to give the correct formulas for several compounds of carbon and sulfur, including carbon dioxide, carbon disulfide, sulfur dioxide, and hydrogen sulfide. Falling back on analogy when experimental evidence was lacking, he reasoned correctly that silica was SiO_2 by comparison with CO_2. He also extended his earlier treatment of metals in the hypothetical gaseous state. He gave molecular weights for (using modern symbols) Hg, Fe, Mn, Ag, Au, Pb, Cu, Sn, Sb, As, K, Na, Ca, Mg, Ba, Al, and Si, based on analyses of the compounds of these elements. His mention of "gaz métalliques" may have done more harm than good to the reception of his hypothesis.

In 1821 Avogadro was able to state the correct formulas of several other compounds including those of phosphorus and the oxides of nitrogen. After deducing the formulas of such inorganic compounds from combining volumes, densities, or merely by analogy, he turned to organic chemistry. He gave the correct empirical formula for turpentine, $C:H = 1.6:1$, (in the symbols of Berzelius $C_{10}H_{16}$) and the correct molecular formulas for alcohol (C_2H_6O) and ether ($C_4H_{10}O$). Berzelius did not arrive at the correct formulas for alcohol and ether until 1828. Berzelius, however, who had developed a theory deriving from both Dalton and Gay-Lussac, took little account of Avogadro.

Avogadro's claim to the hypothesis that is named after him rests on more than his mere statement of it. We have seen that Dalton earlier considered a similar hypothesis but rejected it. Ampère in 1814 independently arrived at a similar conclusion, and later Dumas (1827), Prout (1834), and others formulated the same hypothesis. To Avogadro alone, however, belongs the distinction of applying his hypothesis to the whole field of chemistry.

Ampère's ideas on the constitution of molecules were published in 1814 in the form of a letter to Berthollet. He stated that it was only after writing his memoir that he had "heard that M. Avogadro had used the same idea." Ampère was not primarily concerned with providing an explanation of Gay-Lussac's law. He was interested in the structure of crystals and introduced geometrical considerations which led him to suppose that molecules of, for example, hydrogen, oxygen, and nitrogen each contained four atoms, whereas Avogadro had already shown correctly that these gases contained two atoms per molecule. Despite the inferiority in many respects of Ampère's memoir to that of Avogadro and its clear lack of priority, Avogadro's hypothesis was usually attributed to Ampère until the Italian Cannizzaro called the attention of chemists to the publication of his fellow countryman. Certainly by being published in the *Annales de chimie* Ampère's paper had the greatest possible publicity, and Ampère himself became famous throughout the scientific world after his work on electromagnetism in the 1820's.

In view of the lack of interest shown by chemists in Avogadro's hypothesis, it is all the more noteworthy that he himself continually drew attention to the significance of his ideas. If Avogadro was not heard, therefore, it was not because he had made an isolated pronouncement. He repeated it in a memoir published in 1816 and 1817; and again in two different memoirs published in 1818 and 1819 in Italian publications, he drew attention to his earlier work. The 1819 memoir was later translated into French and the relevant passage reads:

> In considering the matter theoretically and supposing in conformity with what I have established elsewhere (*Journal de Phys. de La Metherie,* July 1811 and February 1814) that in gases reduced to the same temperature and pressure the distances between the centers of the integrant molecules is constant for all gases, so that the density of a gas is proportional to the mass of its molecules. . . .[2]

Even more important was Avogadro's long memoir of 1821: "Nouvelles considerations sur . . . la détermination des masses des molécules des corps." This was published in the memoirs of the Turin Academy of Science, but a summary was published in France in 1826 in the *Bulletin . . . de Ferussac,* and this extract contains a reassertion of Avogadro's hypothesis with the claim that its introduction would do much to simplify and generalize chemistry. Avogadro insisted in this memoir on the necessity of correlating the data obtained by Gay-Lussac on the combining volumes of gases with the theory of fixed proportions—a problem that had been considered only superficially by Berzelius.

From the above it is clear that Avogadro stated his new hypothesis repeatedly over the period 1811–1821. It is true that the later memoirs were particularly long, and only the most relevant parts are included here. More important for the reception of Avogadro's work, however, is that these later memoirs were published in Italy, then at the periphery of the scientific world. When these memoirs were translated into French they appeared not in the influential *Annales de chimie et de physique* but in the comparatively obscure and second-rate *Bulletin . . . de Ferussac.* As regards translation into other languages, not more than three of Avogadro's papers were translated into English and not more than two into German, and the memoirs chosen are not those that we should today regard as significant. Reports on Avogadro's later work were, however, included in Berzelius' *Jahresberichte* from 1832 onward. Some part of the blame for the lack of attention given to Avogadro's hypothesis by his contemporaries must attach to the editors of the influential British, French, and German scientific periodicals.

One of the most remarkable features of Avogadro's hypothesis was the way in which it was neglected by the vast majority of chemists for half a century after its initial publication. The following are some of the reasons for this delay:

(1) It was not clearly enough expressed, particularly in the 1811 memoir. Avogadro did not coin a new term for the "solitary elementary molecules" nor did he use the term *atom.* In any case there was general looseness in the use of the terms *atom* and *molecule,* and they were often used synonymously. It would not have been clear to everyone in the early nineteenth century that Avogadro's hypothesis was quite different from that of Berzelius. Berzelius had substituted atom for volume in cases of combining gases and had ended with the logical contradiction of half an atom. Avogadro overcame this difficulty by introducing a polyatomic molecule, but this concept was quite novel.

(2) Avogadro did not support his hypothesis with any impressive accumulation of experimental results.

He never acquired, nor did he deserve, a reputation for accurate experimental work. Thus, for Regnault, for example, Avogadro was not a brilliant theoretician but merely a careless experimenter.

(3) From the beginning Avogadro applied his hypothesis to solid elements. When experimental evidence was not available, he relied only on analogy. He was correct in considering oxygen and hydrogen as diatomic, but he had little justification in coming to a similar conclusion in the cases of carbon and sulfur. His speculative treatment of metals in the vapor state in his second paper of 1814 cannot have helped his cause. He was, therefore, overly ambitious in extending his hypothesis. (Yet Berzelius too used a "volume theory" not restricted to the gaseous state, and his work did not suffer any eclipse because of this.) There were only a comparatively small number of well-defined substances that existed in the gaseous state and to which Avogadro's hypothesis could be applied. Only with Gerhardt was its full relevance to organic substances appreciated.

(4) The half century after the publication of Avogadro's hypothesis was a time when most attention was paid to organic chemistry, where the primary need was for analysis and classification. Organic analysis was based on weights, not volumes.

(5) Avogadro's idea of a diatomic molecule conflicted with the dominant dualistic outlook of Berzelius. According to the principles of electrochemistry, two atoms of the same element would have similar charges and therefore repel rather than attract each other.

(6) Avogadro, a modest and obscure physicist on the wrong side of the Alps, remained intellectually isolated from the mainstream of chemistry.

Despite the failure of chemists to appreciate the full significance of Avogadro's hypothesis, he could claim in 1845 that his statement that the mean distances between the molecules of all gases were the same under the same conditions of temperature and pressure and the consequence that the molecular weight was proportional to the density was generally accepted by physicists and chemists either explicitly or implicitly.

What was ignored, however, was the use of the hypothesis to determine atomic weights. It was Cannizzaro who, in a paper published in 1858 but not made widely known until 1860 at the Karlsruhe Congress, showed how the application of Avogadro's hypothesis would solve many of the major problems of chemistry. In particular he clarified the relation between atom and molecule which Avogadro had not made explicit. Gerhardt and Laurent had applied the hypothesis with some success to organic chemistry. Cannizzaro performed a roughly complementary task in systematizing inorganic chemistry on the basis of Avogadro's hypothesis. He determined the molecular weights of many inorganic substances and hence the atomic weights. For the first time there began to exist among chemists substantial agreement on atomic weights. Cannizzaro had been able to make use of techniques unknown in Avogadro's time for the determination of the molecular weights of solid elements, including sulfur, phosphorus, and mercury.

Avogadro's first two memoirs to be published, in 1806 and 1807, were on electricity. He considered the state of a nonconductor placed between two oppositely charged elementary layers. If there was air between two charged bodies, it would become charged. In the later terminology of Faraday the claim could be made that Avogadro had some conception of the polarization of dielectrics. In 1842 Avogadro himself claimed that some of Faraday's treatment of condensers was to be found in his own earlier work. At the end of the same memoir Avogadro suggested that the capacity of a condenser was independent of the gas between the plates and that there would be the same process of induction even in a vacuum—a phenomenon later verified by James Clerk Maxwell.

Avogadro's 1822 memoir "Sur la construction d'un voltimètre multiplicateur" was given publicity by Oersted. Avogadro's "multiplier" was one of the most sensitive instruments of the time, and by using it he found that when certain pairs of metals are plunged into concentrated nitric acid the direction of the electric current is momentarily reversed. This happens for the pairs of metals: Pb/Bi, Pb/Sn, Fe/Bi, Co/Sb. This phenomenon had actually been observed in the case of Pb/Sn by Pfaff in 1808, but it was sometimes referred to as "Avogadro's reversal." Avogadro used a succession of pairs of metals with an electrolyte to establish the order Pt, Au, Ag, Hg, As, Sb, Co, Ni, Cu, Bi, Fe, Sn, Pb, Zn, a list that showed several differences from the order found by Volta using a condenser.

Avogadro published his first article dealing only with chemistry in 1809. This memoir, on acids and alkalies, is interesting for several reasons. In the first place it illustrates his abiding concern with chemical affinity and incidentally the great influence exerted on him by Berthollet. Second, in the opening paragraph, which criticizes the oxygen theory of acidity, it illustrates his radical approach to post-Lavoisier chemistry. He postulated a relative scale of acidity in which oxygen and sulfur were placed toward the acid end of the scale, neutral substances in the middle, and hydrogen at the alkali end. A significant feature of this scale was that it was continuous. Avogadro would not allow any absolute distinctions. He was not, for example, prepared to agree with Berzelius that oxygen was absolutely electronegative. Davy, in 1807, had suggested a connection between acidity and alkalinity and electricity; Avogadro developed this idea. Another feature of Avogadro's interests found in this memoir is the subject of nomenclature. He was to give more detailed attention to this in the 1840's.

Avogadro might claim to share with Berthollet the honor of having been one of the founders of physical chemistry in the early nineteenth century. Certainly he saw no boundary between physics and chemistry and made constant use of a mathematical approach. This is exemplified by his various studies on heat; his thermal studies of gases provided a useful approach to physical chemistry. In 1813 Delaroche and Bérard suggested that there was a simple relationship between the specific heat of a compound gas and its chemical composition. Particles of a gas were then envisaged as surrounded by an "atmosphere" of caloric. But the amount of caloric between particles of a gas governed the mutual attraction between its particles. Avogadro thus saw a means of relating chemical affinity to specific heat. Assuming that (specific heat)^m is the attractive power of each molecule and that these attractive powers are additive, Avogadro obtained a number of equations from which m was found to be rather less or rather greater than 2. Taking the deviation from $m = 2$ to be due to experimental error (Avogadro never claimed any high degree of accuracy in his experimental work), he derived the general formula:

$$c^2 = p_1c_1{}^2 + p_2c_2{}^2 + \text{etc.},$$

where c, c_1, c_2, etc. are the specific heats at constant volume of the compound gas and its constituents, respectively, and p_1, p_2, etc. are numbers of molecules of the components taking part in the reaction.

In 1822 Avogadro considered himself justified in making the generalization that the specific heats at constant volume of gases were proportional to the square root of the attractive power of their molecules for caloric. In 1824 he made further progress toward an evaluation of a "true affinity for heat," to which he could assign a numerical value. This value was obtained by taking the square of the specific heat determined by experiment and dividing by the density of the gas, which by Avogadro's hypothesis was proportional to its molecular weight. He thus obtained a series of values ranging from oxygen = 0.8595 to hydrogen = 10.2672. This confirmed his conjecture that oxygen and substances similar to it had the least affinity for heat. He concluded triumphantly that the order so obtained, representing the affinity for heat, coincided with the order in the electrochemical series. He obtained further confirmation by comparing his results with those obtained by Biot and Arago for the relationship between affinity for heat and the refractive indices of gases. Avogadro concluded with a table of twenty-nine substances, headed by acids and terminating with bases. By dividing each affinity for heat by that of oxygen, he obtained a series of what he called "affinity numbers" (*nombres affinitaires*), and in his next memoir he attempted to determine further affinity numbers.

By 1828 he doubted the validity of much of his earlier work on assigning numerical values to affinities, and he therefore reverted to a purely chemical method, developing Berthollet's idea of combining proportions as a measure of affinity. At the end of his life Avogadro claimed that he had succeeded in deriving affinity numbers from atomic volumes and "by a method independent of all chemical considerations"[3]—reminding us of his predominantly physical attitude. By trying to derive chemical information from nonchemical sources, however, he contributed to a situation in which his work lay outside the sphere of interest of contemporary chemists.

In 1819 Dulong and Petit announced that there was a simple relationship between specific heats and atomic weights. Although they suggested that their law might be extended to compounds, it was F. E. Neumann who, in 1831, first applied the law practically to solid compounds. Avogadro, who began his research in this field in 1833, investigated both liquids and solids.

He decided that the formula of a compound in the liquid or solid state could not be the same as that in the gaseous state. He therefore introduced the arbitrary division of molecules and considered, for example, that a molecule of water or ice contained only a quarter as many atoms as one of steam. Thus since H_2O represented steam, water would have been $HO_{1/2}$. (Actually Avogadro says a compound of "1/4 *atom* of hydrogen and 1/4 *atom* of oxygen," but if we interpret "atom" as "molecule" and consider these to be diatomic this would have been the resultant formula.) Mercuric oxide was considered to be 1/2 atom of metal + 1/4 atom of oxygen; aluminum oxide was considered to be 1/2 atom of metal + 3/8 atom of oxygen; ferric oxide was considered to be 1/4 atom of metal + 3/16 atom of oxygen. By such arbitrary division he was able to fit a fairly wide selection of solid compounds into a "law" that he devised to relate specific heat to molecular weight. His 1838 memoir on this subject probably shows Avogadro at his very worst. Fractional atoms were introduced in the most irresponsible way although they were related to the supposed specific heats. The latter soon proved to be inaccurate. Because the memoir was published so long after the first announcement of Avogadro's hypothesis, it was not mentioned earlier as one of the reasons for the rejection of the hypothesis by his contemporaries. Yet the publication of the memoir can only have weakened Avogadro's scientific reputation.

The inaccuracies of the values obtained by Avogadro for specific heats were later criticized by Regnault. We are reminded by such criticism of the opposite poles represented by such men of science as Avogadro and Regnault—the one intuitive, speculative, and theoretical and the other empirical, precise, and practical. Avogadro's research on the vapor pressure of mercury cannot stand comparison for accuracy with Regnault's later work, yet Avogadro deserves credit for being the first to make this determination over the temperature range 100°C.-360°C.

Toward the end of his life Avogadro devoted a total of four memoirs to the subject of atomic volumes. In the first (1843) he pointed out the connection with his classic memoir of 1811—the mean distance between the molecules of all gases is the same under the same conditions of temperature and pressure. In 1824 he had read to the Turin Academy a memoir in which he had pointed out that the atomic volumes (i.e., the volume occupied by the molecule together with its surrounding caloric) of all substances in the liquid or solid state would be the same if it were not for certain factors and in particular the different affinities of bodies for caloric. But the latter factor was directly related to the electronegativity of the element. Comparing the densities of the elements with their atomic weights, he now concluded that the distances between the molecules of solids and liquids, and consequently their volumes, were greater, and hence their densities compared with their atomic weights were less as the body became more electropositive. Alternatively expressed, the atomic volume (atomic weight/density) is greater for the more electropositive elements, and this is now accepted.

Avogadro's work on atomic volumes differs from that of his contemporaries in his insistence on its connection with the position of elements in the electrochemical series. Also his "atomic" volumes were really molecular volumes. In this later work he was as isolated as he had been in his earlier speculations. By his habit of consistently giving references to his own earlier work Avogadro established the lineage of his research with any corresponding priority claim, but the practice had the disadvantage of revealing him as a solitary worker perhaps born a generation too soon.

NOTES

1. Alembic Club Reprint, No. 4, pp. 28-30 (the italics are the author's).
2. *Bulletin . . . de Ferussac*, **5** (1826), 39.
3. *Annales de chimie et de physique*, **29** (1850), 248.

BIBLIOGRAPHY

I. Original Works. Articles by Avogadro include "Considérations sur l'état dans lequel doit se trouver une couche d'un corps non-conducteur de l'électricité, lorsqu'elle est interposée entre deux surfaces douées d'électricités de différente espèce," in *Journal de physique,* **63** (1806), 450-462; "Second mémoire sur l'électricité," in *Journal de physique,* **65** (1807), 130-145; "Idées sur l'acidité et l'alcalinité," in *Journal de physique,* **69** (1809), 142-148; "Essai d'une manière de déterminer les masses relatives des molécules élémentaires des corps, et les proportions selon lesquelles elles entrent dans ces combinaisons," in *Journal de physique,* **73** (1811), 58-76; "Réflexions sur la théorie électro-chimique de M. Berzelius," in *Annales de chimie,* **87** (1813), 286-292; "Mémoire sur les masses relatives des corps simples, ou densités présumées de leurs gaz, &c.," in *Journal de physique,* **78** (1814), 131-156; "Memoria sul calore specifico de' gaz composti paragonato a quello de' loro gaz componenti," in *Biblioteca italiana,* **4** (1816), 478-491; **5** (1817), 73-87; "Osservazioni sulla legge di dilatazione dell'acqua pel calore," in *Giornale di fisica,* **1** (1818), 351-377; "Sopra la relazione che esiste tra i calori specifici e i poteri refringenti delle sostanze gazose" [1817], in *Memorie di matematica e di fisica,* **18** (1818), 154-173; "Sulla determinazione delle quantità di calorico che si sviluppano nelle combinazioni per mezzo de' poteri refringenti" [1817], *ibid.,* pp. 174-182; "Osservazioni sulla forza elastica del vapor acqueo a diverse temperature," in *Giornale di fisica,* **2** (1819), 187-199; "Memoria sulle leggi della dilatazione de' diversi liquidi pel calore," *ibid.,* pp. 416-427; "Memoria sopra lo stabilimento d'una relazione tra le densità e dilatabilità de' liquidi e la densità dei vapori che essi formano," *ibid.,* pp. 443-456; "Memoria sulla legge della dilatazione del mercurio dal calore," *ibid.,* **3** (1820), 24-38; "Nouvelles considérations sur la théorie des proportions déterminées dans les combinaisons, et sur la détermination des masses des molécules des corps," in *Memorie della Reale Accademia delle scienze,* **26** (1821), 1-162; "Sur la manière de ramener les composés organiques aux lois ordinaires des proportions déterminées, *ibid.,* pp. 440-506; "Nuove considerazioni sull' affinità dei corpi pel calorico, calcolate per mezzo de' loro calori specifici" [1822], in *Memorie di matematica e di fisica,* **19** (1823), 83-137; "Sur la construction d'un voltimètre multiplicateur" [1822], in *Memorie della Reale Accademia delle scienze,* **27** (1823), 43-82; "Sur l'affinité des corps pour le calorique, et sur les rapports d'affinité qui en résultent entre eux:-1^er^ Mém." [1823], *ibid.,* **28** (1824), 1-122; **29** (1825), 79-162; "Osservazioni sopra un articolo del Bollettino delle Scienze del sig. B. di Ferussac relativo alle Memorie sull' affinità

dei corpi pel calorico, e sui rapporti d'affinità che ne risultano tra oro," in *Giornale di fisica,* **8** (1825), 432–438; "Mémoire sur la densité des corps solides et liquides, comparée avec la grosseur de leurs molécules et avec leurs nombres affinitaires" [1824], in *Memorie della Reale Accademia della scienze,* **30** (1826), 80–154; **31** (1827), 1–94; "Comparaison des observations de M. Dulong sur les pouvoirs réfringens des corps gazeux, avec les formules de relation entre ces pouvoirs et les affinités pour le calorique" [1826], *ibid.,* **33** (1829), 49–112; "Sur la loi de la force élastique de l'air par rapport à sa densité dans le cas de compression sans perte de calorique" [1828], *ibid.,* pp. 237–274; "Sur les pouvoirs neutralisants des différents corps simples, déduits de leurs proportions en poids dans les composés neutres qui en sont formés," *ibid.,* **34** (1830), 146–216; "Mémoire sur les chaleurs spécifiques des corps solides et liquides," in *Annales de chimie et de physique,* **55** (1833), 80–111; "Sur la force élastique de la vapeur du mercure à différentes températures" [1831], **49** (1832), 369–392; "Nouvelles recherches sur la chaleur spécifique des corps solides et liquides," *ibid.,* **57** (1834), 113–148; "Fisica de' corpi ponderabili, ossia trattato della costituzione generale de' corpi," in *Giornale Arcadio di Scienze,* **79** (1839), 104–107; "Diversi gradi della facoltà elettronegativa ed elettropositiva dei corpi semplice," in *Reunione degli scienziati italiana atti* (1840), 64–65; "Note sur la chaleur spécifique des différents corps, principalement à l'état gazeux," in *Bibliothèque universelle,* **29** (1840), 142–152; "Note sur la nature de la charge électrique," in *Archives de l'électricité,* **2** (1842), 102–110; "Saggio di teoria matematica della distribuzione della elettricità sulla superficie dei corpi conduttori nell'ipotesi della azione induttiva esercitata dalla medesima sui corpi circostanti, per mezzo delle particelle dell'aria frapposta" [1842], in *Memorie di matematica e di fisica,* **23** (1844), 156–184; "Proposizione di un nuovo sistema di nomenclatura chimica" [1843], *ibid.,* pp. 260–304; "Mémoire sur les volumes atomiques, et sur leur relation avec le rang que les corps occupent dans la série électro-chimique" [1843], in *Memorie della Reale Accademia delle scienze,* **8** (1846), 129–194; "Mémoire sur les volumes atomiques des corps composés" [1845], *ibid.,* pp. 293–532; "Note sur la nécessité de distinguer les molécules intégrantes des corps de leurs équivalents chimiques dans la détermination de leurs volumes atomiques," in *Archives des sciences physiques et naturelles,* **11** (1849), 285–298; "Sopra un sistema di nomenclatura chimica" [1847], in *Memorie di matematica e di fisica,* **24** (1850), 166–211; "Troisième mémoire sur les volumes atomiques. Détermination des nombres affinitaires des différents corps élémentaires par la seule considération de leur volume atomique et de celui de leurs composés" [1849], in *Memorie della Reale Accademia delle scienze,* **11** (1851), 231–318; "Quatrième mémoire sur les volumes atomiques. Détermination des volumes atomiques des corps liquides à leur température d'ébullition" [1850], *ibid.,* **12** (1852), 39–120; "Mémoire sur les conséquences qu'on peut déduire des expériences de M. Regnault sur la loi de compressibilité des gaz" [1851], *ibid.,* **13** (1853), 171–242.

In addition Avogadro wrote the major treatise: *Fisica de' corpi ponderabili ossia trattato della costituzione generale de' corpi,* 4 vols. (Turin, 1837–1841).

II. SECONDARY LITERATURE. V. Cappelletti and A. Alippi, "Avogadro," in *Dizionario biografico degli Italiani,* IV (Rome, 1962), 689–707; N. C. Coley, "The Physico-Chemical Studies of Amedeo Avogadro," in *Annals of Science,* **20** (1964), 195–210; I. Guareschi, "Amedeo Avogadro e la sua opera scientifica. Discorso storico-critico," in *Opere scelte di Amedeo Avogadro pubblicata dalla R. Accademia delle scienze di Torino* (Turin, 1911), 1–140; A. N. Meldrum, *Avogadro and Dalton. The Standing in Chemistry of Their Hypotheses* (Edinburgh, 1904); L. K. Nash, "The Atomic Molecular Theory," Case 4 of *Harvard Case Histories in Experimental Science,* J. B. Conant, ed., Vol. I (Cambridge, Mass., 1957); J. R. Partington, *A History of Chemistry,* Vol. IV (London, 1964).

M. P. CROSLAND

IBN AL-ʿAWWĀM ABŪ ZAKARIYYĀ YAḤYĀ IBN MUḤAMMAD (*fl.* Spain, second half of the twelfth century; nothing more is known of his life), *agronomy.*

Ibn Khaldūn mentions Ibn al-ʿAwwām in his *Muqaddima* as the author of a treatise on agriculture, the *Kitāb al-filāḥa,* which was, according to him, a summary of the *Nabatean Agriculture* of Ibn Waḥshiyya. The work of Ibn al-ʿAwwām, published in Spanish at the beginning of the nineteenth century, consists of thirty-five chapters, of which thirty are devoted to agronomy and the rest to related matters. It deals with 585 plants and more than fifty fruit trees, and is generally limited to a repetition of the doctrines of his predecessors, although there are a few observations, made by Ibn al-ʿAwwām in the Aljarafe of Seville, that are introduced by the term *lī.*

Among the classical writers he mentions Democritus, the Pseudo Aristotle, Theophrastus, Vergil, Varro, and especially Columella (the format of the *Kitāb al-filāḥa* is similar to that of the *De re rustica*). The Oriental Arabs are represented by Abū Ḥanīfa al-Dīnawarī (the tenth-century botanist who wrote the *Kitāb al-nabāt*) and the *Nabatean Agriculture.* The most extensive quotations, however, are from the Hispano-Arab agriculturists, among them Albucasis, possibly the author of a *Mukhtaṣar kitāb al-filāḥa;* the Sevillian Abū ʿUmar ibn Ḥajjāj (*d. ca.* 1073), author of the *Muqniʿ;* Ibn Baṣṣāl, a Toledan who was the director of the botanical garden of al-Maʾmūn and later that of al-Muʿtamid, as well as author of the *al-Qaṣd wa'l-bayān*; Abū'l-Khayr al-Shajjār of Seville; and Abū ʿAbd Allāh Muḥammad al-Tijnarī, author of the *Zahr al-bustān wa-nuzhat al-adhhān.* Most of the works of these authors were known, until