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JOSIAH WILLARD GIBBS[1]

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ON the one hundredth anniversary of his birth, we are here to do honor to the memory of Josiah Willard Gibbs, the greatest physical scientist that America has produced and one of the greatest original thinkers of all time. The occurrence of genius is commonly believed to be a phenomenon of pure chance, and such it may well be so far as native talent is concerned; but talent has merely a potential value; it is fruitful only when it is properly cultivated, indeed, we may say when it is self-cultivated under favorable conditions. Genius may be assisted in this process of self-cultivation but, in all cases, genius flourishes best in an environment of complete intellectual freedom. The history of American science bears this out.

Let us review, briefly, the careers of the American men of genius who contributed to the development of physical science from Colonial times up to the last quarter of the nineteenth century. Up to 1880, America had produced five great physical scientists: Benjamin Franklin, Benjamin Thompson (Count Rumford), Joseph Henry, Henry A. Rowland and Josiah Willard Gibbs.

Franklin and Rumford were products of pre-revolutionary America; they were self-taught, having received only very meager common school education. The two men, although their lives were, in certain respects, very diverse, had much in common. Both were exceptionally versatile; both were keen observers and ready experimenters; both were of a practical and inventive turn of mind; both were keenly conscious of their social environment and both did much to advance science and learning in other ways than through their scientific contributions. Franklin was active in promoting the establishment of libraries, colleges and

[1] An address delivered in Yale University on the occasion of exercises held in commemoration of the one hundredth anniversary of the birth of Josiah Willard Gibbs.

learned societies—notably, the American Philosophical Society; Rumford founded the Royal Institution, whence came the epoch-making researches of Davy and Faraday.

Joseph Henry received his formal education, such as it was, at Albany Academy. He began his scientific work while a teacher at the Albany Academy, where he remained until 1832 when he removed to Princeton. In 1846, he resigned his professorship at Princeton to become the first secretary of the newly founded Smithsonian Institution. Henry began his researches in electromagnetism while in Albany and continued them at Princeton. He was a genius of first rank, but his work has been rather overshadowed by that of Faraday.

Henry A. Rowland prepared for college, or attempted to do so, at Newark Academy. Although a brilliant student in other subjects, he had a keen distaste for Latin which he was unable to overcome. After a final unsuccessful effort to master Latin and Greek, at Andover, and lacking the necessary knowledge of these subjects for college entrance, Rowland entered the Rensselaer Polytechnic Institute, where he remained for three years. He then spent a year in the Sheffield Scientific School, at Yale, and returning to the Rensselaer Polytechnic Institute, he received his baccalaureate degree in civil engineering from that institution in 1870. Rowland was nine years younger than Gibbs, but his scientific work was contemporaneous with that of Gibbs's. Rowland's first great undertaking was an accurate redetermination of the mechanical equivalent of heat, the first determination of which had been made by Count Rumford three quarters of a century earlier. In the field of heat, American scientists have made greater contributions than in any other branch of physical science. It might be said that Rumford began the solution of the problem of heat, and Gibbs completed it.

Gibbs entered Yale College in 1854, after preparing at the Hopkins Grammar School of New Haven. He was evidently proficient in the classical languages, since, as an undergraduate at Yale, he took prizes in Latin and gave a Latin oration on graduating. He seems to have had an equal facility in mathematics, for he likewise took prizes in that subject. After graduating from Yale, in 1858, he entered the graduate school, where, after five years, he received his doctorate in 1863. After spending the following three years as a tutor in Yale College—two in Latin and one in natural philosophy—Gibbs went abroad, spending the winter of 1866–67 in Paris; the summer and winter of 1867–8 in Berlin and the summer and winter of 1868–9 in Heidelberg. He returned to America in June, 1869, and for two years thereafter seems to have had no academic connections. In 1871 he was appointed professor of mathematical physics in Yale University, which position he held until the time of his death, on April 28, 1903.

It is an interesting fact, and it would seem a significant one, that of the five men, native of America, who achieved distinction in physical science, two were self-taught, one received his education in a small academy and a fourth in a technical school; only one was the product of one of our better American colleges. Is it that men of potential genius did not enter the numerous American colleges during the Colonial and the post-revolutionary periods or is it that the course of training which these colleges thought fit to impose upon their students unfitted them for great achievement? Is the probability not that, while men of genius in America were able to overcome the handicap of lack of means, lack of education and lack of technical training, they were not able to resist the blighting influence of eighteenth and nineteenth century scholasticism? Gibbs, alone, stands out as a notable exception. May it have been that there was something in the organization of Yale College that permitted Gibbs to cultivate his mind and to find free scope for his brilliant intellect? With his ready facility in the ancient languages and, doubtless, in other subjects as well, and with his excellent preparation, Gibbs probably found much time in which to inform himself on subjects that did not appear in the curriculum of Yale in his day. It is also a notable fact that he spent five years in the Yale graduate school, the first organization of this kind in America. Here, without doubt, Gibbs found further opportunity to follow his own bent. His experience as a tutor can hardly have been a profitable one; his mind, obviously, was not interested in the classics, and there is little doubt but that Gibbs was much more interested in the development of science than he was in teaching undergraduates. Later, when he was professor of mathematical physics, he never showed any inclination to simplify his presentation of a subject or to give introductory courses for students who were not prepared for subjects as he presented them.

During his stay abroad, Gibbs must have informed himself very widely with respect to the physical sciences and trained himself in mathematics. The records show that, while in Berlin, he attended lectures in physics and technology, under Magnus; acoustics, under Kundt; electricity and electromagnetism, optics, acoustics and capillarity, under Quincke; determinants and analysis, under Weierstrass; quadratic forms and probability calculations, under Kronecker; and least squares, under Foerster. It is not known what lectures he attended while in Heidelberg, but, judging by the lectures that he attended in Berlin, it is safe to say that he attended many lectures under the notable men who were at the University of Heidelberg at that time. These included: Professors Rummer, Cantor, Hesse and Drs. Lüroth, Weber, du Bois Raymond and Eisenlohr, in mathematics, and Professors Kirchhoff, Helmholtz, Bunsen, Kopp and Dr. Horstmann, in physics and chemistry.[2]

Examining the record, we see that between 1858, when he graduated from Yale College, and 1871, when he entered upon his professorship of mathematical physics in Yale University, Gibbs spent ten years in preparation for his life work, not counting the three years which he spent as tutor in Yale College. The conclusion that one may draw from this is that the preparation which our American colleges afforded men of science in the nineteenth century was not necessarily fatal to the development of their genius, provided that they were able to devote sufficient time to their training afterwards. Gibbs, fortunately, was financially independent and was, therefore, able to follow his own bent. This was not true of the great mass of men in that day, as it is not true of the great mass of men in our colleges to-day. We may well ask ourselves the question: Are our colleges quenching the genius of our outstanding students through the formal curricula that they impose upon them and through the lack of opportunity for their self-development?

By training and tradition and by the force of the environment in which he was placed, Gibbs should have developed into a typical exponent of nineteenth century scholasticism. That he did not become such was in part due to his own intellectual and financial independence and in part, without doubt, to certain favorable conditions that existed at Yale in the 1850's and 60's.

Gibbs, like Franklin and Rumford, had a strong leaning toward science, with a turn toward invention; in 1866, while still a tutor in natural philosophy in Yale College, he invented a brake for railway cars and secured a patent for the same in April of that year.[3] At about that time, also, he invented a new type of governor of a higher order of approximation to astaticism than any of its predecessors. This governor was constructed in the shops of the Sheffield Scientific School and is in the collection of the Department of Physics of Yale University.[4] Until we have come to know that Gibbs was endowed with a mind which possessed a keen appreciation of and interest in things physical and practical, his life and works remain a profound mystery. Possessing intellectual powers of the highest order, as much at home in pure mathematics as in physics and chemistry, Gibbs constantly exercised his will to direct his thoughts along lines that lay within the framework of material phenomena.

It has often been stated that Gibbs never carried out an experiment. This statement is not borne out by the facts; it is known that Gibbs constructed some apparatus in his own home.[5] According to Professor Charles S. Hastings, in his Biographical Memoir on Gibbs in the National Academy of Sciences, Gibbs carried out an optical experiment. How many other experiments he may have carried out, no one can say, for Gibbs communicated to others only the results of major investigations. Speaking of this experiment, Professor Hastings, after reviewing its general purpose, says:

> . . . the tentative explanation, however, involved the occurrence of certain phenomena in specular reflection which had never been seen or, at last, recorded. As it did not seem to him that such negative evidence was conclusive, he constructed an apparatus with his own hands so perfectly adapted to the end in view that his observations afforded the proof sought. A striking light is thrown upon the character of the great physicist by the fact that no reference to this theory, which must have cost much critical study, appears in his writings, nor is it known that anyone except the present writer ever saw the apparatus and made the experiment for which it was designed.

In the main, Gibbs depended upon experimental results available in the literature for data with which to test his theoretical investigations. That he was familiar with the literature and quick to make use of results there available is shown by examples that appear in his treatise of 1876–8, as well as in numerous subsequent papers. His chief interests were theoretical, and his physical sense was so keen that he could frame correct physical concepts with a minimum of experience with the phenomena themselves. In this Gibbs was highly exceptional; he introduced many new and exact concepts into science long before any observations relating to them had been made.

For fifty years, now, we have been hearing much and often about the manner in which American science, in general, and Yale University, in particular, failed to recognize Gibbs and his works. The explanation is

2 There is no certain record of what lectures Gibbs attended in Paris, but Gibbs's own copies of lists of courses offered at the Sorbonne bear pencil marks against certain courses which were probably the ones Gibbs expected to attend, and perhaps did attend up to the time of his illness while in Paris. The marked subjects are: *Astronomy*, Puiseaux; *Calculus of Probability and Mathematical Physics*, Lamé or Briot; *Physics*, P. Dessains; *Rational Mechanics*, Liouville; *Differential and Integral Calculus*, Serrer; *Chemistry*, Balard. (For the information concerning Gibbs's studies while abroad, the writer is indebted to Professor R. G. Van Name, of Yale University.)

3 U. S. Patent No. 53,931, April 17, 1866.

4 Charles S. Hastings, Biographical Memoirs, Nat. Acad. of Sci., 6: 375, 1909. It is interesting to note that among Gibbs's papers was found a manuscript entitled "On the Form of the Teeth of Wheels in Spur Gearing." It has been suggested that this was a copy of Gibbs's thesis for the doctorate, but this is not certain; it does, however, bear witness to Gibbs's early interest in mechanical problems.

5 Professor Van Name reports an apparatus that Gibbs so constructed for an optical experiment, but it is not known what the nature of this experiment was.

simple: Gibbs was half a century in advance of his time and American scientists of his day were ill-prepared to comprehend the abstract philosophical results of Gibbs's theory. Much the same thing was true throughout the world; it seems that at the time of their publication, or soon thereafter, only two men comprehended the significance of Gibbs's work. One was Clerk Maxwell, who immediately called attention to the first two papers of Gibbs; in his "Theory of Heat," Maxwell incorporated a chapter dealing with the Gibbs surface. As is well known, Maxwell constructed several models of this surface with his own hands, one of which he sent to Gibbs. Maxwell also called attention to Gibbs's later paper of 1876. Had Maxwell lived, Gibbs's theory would have become known to the scientific world much earlier than it was.[6] Another physicist who early recognized the significance of Gibbs's contributions was J. D. van der Waals, Sr. He called Roozeboom's attention to the paper on heterogeneous equilibria, and this led to the development of the phase rule in the hands of Roozeboom and his associates. Van der Waals, himself, throughout his life, was active in developing the consequences of Gibbs's theory, as is evident from his admirable text with Kohnstamm, entitled "Lehrbuch der Thermodynamik," published in two parts, the first in 1908 and the second in 1912.

That Gibbs's ability was recognized at Yale University is evident from the fact that he was appointed professor of mathematical physics in 1871 before he had published a single paper. Gibbs was early recognized by his contemporaries in America, being elected to the National Academy in 1879 and awarded the Rumford Medal in 1881. It is true, however, that while Gibbs's ability was generally recognized by his American contemporaries, his scientific contributions were not understood.

How Gibbs came to interest himself in the thermodynamics is not known; that he should have done so is not surprising. The two fields of physics that engaged the attention of physicists during the greater part of the nineteenth century were electromagnetic phenomena and phenomena relating to heat. Judging by the subjects upon which he lectured during 1871–2 and 1872–3, Gibbs at that time was interested in physical optics, particularly the elastic solid theory. According to Hastings, he arrived at the conclusion that the obstacles in the way of this theory were insuperable. Later, he was a proponent of the electromagnetic theory of Maxwell at a time when many other eminent physicists were reluctant to accept it.

6 It is of interest to note that Rowland's first paper on the magnetic circuit was not accepted for publication by American editors. Rowland sent the paper to Maxwell, who recognized its value and sent it to the *Philosophical Magazine*, where it was published immediately, Maxwell himself reading the proof in order to avoid delay. Only another genius can recognize genius.

Phenomena relating to heat were intensively cultivated by physicists from 1842 onward. The classical researches of Rumford had been forgotten for nearly half a century, when they were independently repeated and extended by Joule between the years 1837 and 1843. Mayer published his paper on the equivalence of heat and work in 1842. As early as 1824, Carnot had enunciated his celebrated principle,[7] now known as the second law of thermodynamics, but the significance of Carnot's principle was not recognized until the relation between heat and work had been clarified in the 1840's. The concept of absolute temperature was established in two papers by Sir William Thomson in 1848 and 1851. In 1851, Clausius combined the principle of Carnot with the principle of the conservation of energy, which, by then, had been well established through the experiments of Joule. Thereafter, many physicists were active in developing the elements of thermodynamics, applying the two principles—that of Carnot and that of the conservation of energy—almost exclusively to one-component systems. Clausius introduced the entropy concept in 1865. By 1870, the framework of thermodynamics had been erected and its application to one-component systems developed. The literature relating to thermodynamics was, however, in a state of confusion; concepts were not clear, physical quantities were not well defined and the mathematical manipulations were cumbersome and unsuited for the purpose of describing the thermodynamic properties of physical systems generally.

It was natural that Gibbs, who doubtless was well acquainted with the literature of his day, should have become interested in a field where it was apparent that much remained to be done. In his first two papers of 1873, he developed the methods and forged the tools that he later used in treating physical systems from a very general point of view. He introduced the entropy concept and showed that a better description of phenomena is obtained by means of the energy-entropy-volume relation than by means of the pressure-temperature-volume relation. He showed how the state of a body may be represented by means of the energy-entropy-volume surface, every point of which corresponds to a definite state of the substance. He showed how, by means of this surface, the boundary between stable and metastable states may be readily traced, as also the boundary between metastable and unstable states, and showed, moreover, how states capable of existing in equilibrium with one another may readily be derived from the surface. By means of this surface, it is possible, at a glance, to obtain a picture of all the possible states of a physical system.

The first two papers were only preliminary to the

7 Carnot's principle states that it is impossible to transfer heat from a lower temperature to a higher without the performance of work or, otherwise, leaving compensating changes in the system or its surroundings.

third, which appeared in two parts in 1876 and 1878, respectively; in these, Gibbs treated systems comprising any number of substances—which might or might not interact with one another—existing in any number of homogeneous parts or states of aggregation.

Previous to Gibbs, the concept of reversibility, which means equilibrium at all points of a process, was clear, but the concept of equilibrium in a heterogeneous system was still vague. For very simple systems, such as water, the equilibrium conditions were recognized and James Thomson had shown that at the natural freezing point of water, three monovariant systems meet. The concept of equilibrium in a highly complex system, involving any number of component substances, had not been touched upon prior to Gibbs. Obviously, before being able to attack this general problem of equilibrium, it was necessary to have a criterion of equilibrium. Gibbs was well versed in mechanics, and it was, therefore, natural that he should seek for some general principle, similar to the principle of virtual displacements in mechanics, which might be applied to chemical systems. That he was influenced by the earlier work of Clausius seems certain, for at the head of his treatise "On the Equilibria of Heterogeneous Substances," he quotes a couplet from Clausius:

> Die Energie der Welt ist konstant.
> Die Entropie der Welt strebt einem Maximum zu.[8]

The statements of Clausius are physically meaningless. Gibbs formulated the underlying idea in a form such that it could be applied to real physical systems. He states the condition for equilibrium alternatively as follows:

> I. For the equilibrium of any isolated system it is necessary and sufficient that in all possible variations of the state of the system which do not alter its energy, the variation of its entropy shall either vanish or be negative.
>
> II. For the equilibrium of any isolated system it is necessary and sufficient that in all possible variations in the state of the system which do not alter its entropy, the variation of its energy shall either vanish or be positive.

We know nothing about the energy and the entropy of the universe; we have knowledge only of finite physical systems which we can place under observation and over which we have control; therefore, Gibbs limits his system to what he terms an "isolated system" and applies his criteria for equilibrium, which follow directly from the first and second laws of thermodynamics. Gibbs shows that the two criteria, as stated above, are strictly equivalent.

Having set up criteria of equilibrium, it was necessary to define the various thermodynamic quantities, particularly the energy and entropy in terms of the variables that fix the state of the system. The concept of an equation of state was not thoroughly familiar to physicists in Gibbs's day, although it is clear that, since Andrews had already carried out his classical experiments with carbon dioxide and James Thomson had already arrived at the p,v,T surface as representing the possible states of a system, it was generally understood that the state of a simple substance is determined by these three variables. Gibbs, in his earlier paper, had shown that Thomson's representation is incomplete and that certain important thermodynamic quantities may not be derived from such a surface. It was for this reason that he introduced the energy-entropy-volume surface which gives a complete description of all thermodynamic properties of a substance.

In the case of a system containing any number of substances, it was not obvious what variables fix the state of the system. Gibbs assumed (implicitly) an equation of state involving pressure, temperature and the relative amounts of the independently variable substances present. It was then necessary to derive an expression connecting the changes in energy with changes in entropy, volume and the amounts of the various substances in the different homogeneous aggregations of matter. To do this, he introduced a new concept, namely, the thermodynamic potential, which is the derivative of the energy with respect to the mass of a given component, other variables remaining constant, so that for a given homogeneous aggregation of matter, the energy is related to the variables which fix the state of the system by a differential equation of the form:

$$d\varepsilon = Tds - pdv + \mu_1 dm_1 + \mu_2 dm_2 \; . \; . \; . + \mu_n dm_n$$

where the μ's are the thermodynamic potentials of the various substances present and ε, s and v are the energy, entropy and volume, respectively, and the m's are the masses of the constituent substances. The thermodynamic potentials, μ, together with entropy and volume, are functions of the variables T, v and the masses, m_1, m_2, . . . m_n, of the constituent substances in the different aggregations of matter which comprise the system. It is understood that the masses are independently variable and that substances may be present other than those which have been chosen as independent variables; but whatever variables may be chosen, they must be independent. Gibbs next assumed that, for a heterogeneous system, the total energy of the system is made up of the sum of the energies of all the different homogeneous parts which exist in equilibrium with one another or, as he says, *coexist*. The various homogeneous aggregations of matter, each of which has a definite equation of state, he calls *phases* and two aggregations of matter, having the same equation of state, belong to the same phase. The independently variable substance he calls *components*. What particular substances are chosen as components is arbi-

[8] The energy of the universe is constant. The entropy of the universe approaches a maximum.

trary so long as they are always independent and serve to build up all the different phases of the system.

Having arrived at a means of defining the energy and entropy of the system, Gibbs proceeds to apply his criterion for equilibrium, namely, that the energy of the system shall be a minimum under the conditions that the total volume, the total entropy and the total masses of the several components of the systems remain constant. This leads to the result that equilibrium obtains in the system when the temperature of any one phase is equal to the temperature of any other, the pressure of any one phase is equal to the pressure of any other and the thermodynamic potential of any one component in any one phase is equal to the thermodynamic potential of the same component in every other phase.

The variables of the system are the temperature, the volume and the relative amounts or concentrations of the several components in all the different phases; in order that equilibrium shall be established, these variables must adjust themselves in such a way that the condition for equality of the thermodynamic potentials of the several components throughout the system is fulfilled. This condition of equality of the thermodynamic potentials of each of the several components in the different phases thus represents a multiplicity of conditions which must be satisfied by the variables; and when the number of independent conditions is equal to the number of variables, the system is completely fixed or, as we say, is *invariant*. Gibbs showed that a system will be invariant when the number of phases, r, is equal to the number of components, n, increased by two, or algebraically, when $r = n + 2$. When the number of phases is only one greater than the number of components ($r = n + 1$), one variable of the system may be fixed arbitrarily at any desired value within the physical limits of the system; such a system is said to be *monovariant*. When $r = n$, two variables may be arbitrarily fixed and the system is said to be *bivariant*.

We may illustrate the phase rule in the case of a system built up of only one substance, that is, a system of one component. Consider a system composed of pure water. Three phases (three different states of water) may coexist at a certain temperature which is an invariable property of water. We may, for example, have water vapor, liquid water and ice coexisting at the triple point, which is 0.0076° above 0° on the Centigrade scale, and at that temperature only. If the temperature is increased, ice melts and we have an equilibrium between liquid water and water vapor which may exist at a series of temperatures and pressures. If the temperature is lowered, liquid water freezes and we have a similar equilibrium between ice and water vapor; if the pressure is increased, vapor is condensed and we have an equilibrium between ice and water, the temperature diminishing with increasing pressure. At higher pressures, a new form of solid water (ice_{II}) appears and we have an invariant equilibrium between ice_{I}, ice_{II} and liquid water.

Gibbs also considered equilibria in systems in which reactions occur among various of the molecules present. He derived a relation governing the equilibrium in such systems and showed how, in the case of dilute systems, this leads to a simple relation between the concentrations of the various substances concerned in the reaction. In brief, Gibbs, from thermodynamic considerations, derived the law of mass action which had earlier been arrived at by Guldberg and Waage on the basis of kinetic considerations. He showed, moreover, how this equilibrium depends upon temperature. In the earlier chapters of his treatise, Gibbs considered external forces to be excluded from his system; later he investigated what modifications are required when external forces act. He thus investigated the action of gravitational force, of electrical forces and surface forces. Very important was his treatment of systems under the action of electrical forces; he showed, what was not then recognized, that in such systems the energy change is not equal to the work done against the external forces, but, rather, that it is equal to the sum of two terms: (1) the reversible work done against the external forces and (2) the reversible heat change which is equal to the product of the absolute temperature and the entropy. In these considerations, he anticipated Helmholtz, who arrived at much the same result in 1882. Even more important and original were Gibbs's contributions in the field of surface forces. Here Gibbs invented entirely new concepts which had never been thought of before and which have since been found indispensable in describing phenomena that occur at the boundary between two phases of multicomponent systems.

It is not possible to give an adequate picture of Gibbs's contributions in brief form. His papers on thermodynamics cover some 400 pages and are written in a highly condensed, although elegant, style. An adequate commentary on the thermodynamic theory of Gibbs would require several thousand pages.[9] Nor are Gibbs's contributions to thermodynamics his only important contributions; he was active in many other fields, particularly in vector analysis, multiple algebra and the electromagnetic theory. The most important of his other contributions, however, is his treatise on statistical mechanics, which was published in 1902. Here, as in his treatise on thermodynamics, he reduces his assumptions to the very minimum and arrives at results of the greatest generality.

The generalizations of Gibbs concerning heteroge-

[9] Compare, for example, "Commentaries on the Scientific Writings of J. Willard Gibbs," Volume I, Thermodynamics, Yale University Press, New Haven, 1936.

neous equilibria have exercised an influence upon chemistry which is second only to that of the law of the conservation of mass. Although some of the relations that follow from Gibbs's theory were subsequently discovered independently by other investigators, these were derived in a much less general manner than by Gibbs, and not infrequently they were applied when limiting assumptions (often implied) were not fulfilled and the results obtained were misleading. At the time of Gibbs, chemists concerned themselves very little with the physical properties of chemical systems; physical chemistry, as such, had not yet come into being and chemists were largely concerned with the development of organic chemistry. As physical chemistry developed during the 1880's, and later, Gibbs's work gradually came to the notice of physical chemists and the thermodynamics of Gibbs slowly replaced the earlier and less rigorous and elegant formulations. Except for certain new material and many examples, all of which fit into the framework of Gibbs's theory, modern texts on thermodynamics are essentially commentaries on Gibbs's thermodynamical theory.

Of all the relationships following from Gibbs's thermodynamical theory, the simplest and, at the same time, the most general, is the phase rule. With the aid of the phase rule, it is possible to arrive at a knowledge of the constitution of material systems and the relation of various parts of such systems to one another without destroying the systems themselves. In many respects, it is a more powerful tool than is chemical mass analysis, which is useful only if the systems in question may be resolved into their component parts without changing their nature and composition. In the case of metallic systems, for example, which are frequently very complex and the component parts of which can not be separated from one another by analytical means, the phase rule enables us to determine the composition and number of substances present and the influence which these substances have on the properties of the material in question. Take such a simple case as that of carbon steel: here we have to do with iron in its several forms, together with several kinds of solutions of carbon in iron and with free carbon. Mass analysis enables us only to determine the gross composition of the steel; with the aid of the phase rule, we can determine the different kinds of substances present, how they may be transformed into one another by change of conditions, and how the properties of the steel depend upon the various substances present and the history of the sample of steel.[10] As an example, however, carbon steel is an oversimplified case of a metallic system; modern steels are extremely complex, containing, in addition to carbon, various amounts of such elements as tungsten, molybdenum, tantalum, uranium, chromium, nickel, silicon, titanium and many others. The detailed structure of these steels has been determined with the aid of the phase rule.

What is true of the alloys of iron is true of the innumerable alloys of other metallic elements such as magnesium, aluminum, zinc, copper, tin, nickel, chromium, antimony, bismuth, platinum, gold and the like. These alloys have proved invaluable in modern industry. Except for the availability of such alloys designed to meet the needs of special conditions, modern machines, such as the automobile, the aeroplane and the streamlined railway train, would not be practical.

The phase rule finds application, also, in the ceramics industry, in the cement industry and, particularly, in the chemical industry. In the oil industry, for example, it is necessary to separate very complex liquid mixtures into various components having desirable and necessary properties. The present art of the separation of hydrocarbon oils, by distillation, by solvent extraction and by other means, is based upon the phase rule.

I have discussed the phase rule somewhat in detail, as an example, but Gibbs's theory leads to many other important consequences. The laws governing the equilibrium in reacting systems follow directly from this theory. So, also, Gibbs's theory provides a foundation for the treatment of colloidal systems. Much remains to be done in this field, but Gibbs has provided the fundamental concepts by means of which the problems of colloid chemistry may ultimately be resolved. The unravelling of the nature of living systems, which are largely colloidal in nature, involves surface phenomena that are amenable to Gibbs's theory.

Because Gibbs was a man of retiring disposition and was very much preoccupied with his important researches, he had no large circle of friends and entered into no active correspondence with other investigators. We may, therefore, be misled into undervaluing Gibbs's versatility and his ability in directions other than those which he chose to follow.[11] A paragraph from the Biographical Memoir of Josiah Willard Gibbs by Pro-

[10] The phase rule is normally applied in conjunction with other physical observations such as crystalline structure, electrical, magnetic and mechanical properties.

[11] A number of statements in the literature relating to Gibbs are without foundation. Such a one is the statement that he was a student of Clausius. Clausius was at Wurtzburg when Gibbs was at Heidelberg and there is nothing to indicate that Clausius and Gibbs ever met. Another statement that gives quite an erroneous impression of Gibbs's character and of his home relations is to the effect that Gibbs was pressed into service by his sister to drive the family carriage because her husband, who was librarian at Yale, was too busy to do this. The truth of the matter is that Gibbs took very little exercise, walking only between his home and his office in the Sloane Laboratory. The members of his family, therefore, took advantage of every opportunity to induce Professor Gibbs to get out of doors. He rather enjoyed driving the family carriage and occasionally rode horseback as well.

fessor Hastings throws much light on this situation. He writes:

> It will surprise no reader of the numerous biographical notes concerning Professor Gibbs to learn that a man of so judicial a temperament was a very successful man of affairs. Happily for science, his position in the University was not such as to render that fact conspicuous, else he might have been called upon for work which, in view of his consciousness (conscientiousness) and inherent modesty, could easily have seriously interfered with his scientific pursuits. He did, however, give his services as a trustee to the affairs of the Hopkins Grammar School of New Haven, and he acted for many years (17) as treasurer of its funds, which had come down in part from colonial times.

Gibbs was extremely painstaking in everything that he did and pronounced judgment only after mature consideration. In faculty meetings, he spoke seldom, but when he spoke, it was to the point. It is said that on one occasion, after a lengthy discussion as to the relative merits of the languages and mathematics, Gibbs said: "Mathematics is a language too." Gibbs was kindly in disposition, considerate and ready to be of help to his students. He had a sense of humor and smiled easily. He never sought for honors or advancement except as they came through recognition of his work. Such honors came to him in great abundance. They need not be enumerated here; I mention only the Copley Medal awarded him by the Royal Society of London, in 1901. He was made an honorary member of nearly every scientific organization of note and received honorary degrees from many of the leading universities of the world.

Outstanding qualities of Gibbs's character are his modesty and his devotion to science. He had not a few traits in common with Michael Faraday. At the beginning of the most productive period of his career, Faraday renounced all consulting work, from which he derived an income of from 500 to 1,000 pounds per annum—his salary at the Royal Institution was 100 pounds; for nine years following his appointment as professor of mathematical physics at Yale, Gibbs served without compensation. Gibbs, like Faraday, had great physical insight. Faraday, without mathematical training, invented the concept of the electromagnetic field, which later provided Maxwell with the foundation for the electromagnetic theory; Gibbs, with little experience with material systems, invented new physical concepts, that have served as a basis for the development of chemistry during the past fifty years.

Of the inner workings of Gibbs's mind, we know little; he left behind few letters and no notes. We can best judge the quality of the man by what he said of his colleague, Hubert Anson Newton, in the Biographical Memoir which he wrote for the National Academy of Sciences. Here, in speaking of his friend, he unconsciously reveals himself. After discussing Professor Newton's scientific contributions, Gibbs writes:

> But these papers show more than the type of mind of the author; they give no uncertain testimony concerning the character of the man. In all these papers we see a love of honest work, an aversion to shams, a caution in the enunciation of conclusions, a distrust of rash generalizations and speculations based on uncertain premises. He was never anxious to add one more guess on doubtful matters in the hope of hitting the truth, or what might pass as such for a time, but was always ready to take infinite pains in the most careful testing of every theory. With these qualities was united a modesty which forbade the pushing of his own claims and desired no reputation except the unsought tribute of competent judges.

These words of Gibbs characterize Gibbs himself much more truly than anything that I might hope to say.

OBITUARY

PROFESSOR S. P. L. SORENSEN

THE American students who were privileged to work with Professor Sørensen and the many who found inspiration in his scientific articles regret the death of this distinguished scientist on February 12.

Sørensen succeeded Kjeldahl as director of the chemical division of the Carlsberg Laboratory, in Copenhagen. Each of these men, in addition to many other contributions, hit upon something that has made his name a household word in chemical laboratories.

It would be trivial to say that Sørensen introduced the symbol p_H^+ for a unit in a scale of acidity. The significance of the fact that this symbol has become almost as common as that for degree centigrade pertains to an aspect of science that too often is neglected. By means of his logarithmic scale Sørensen was able to place on one chart or one sort of chart several of the relations in acid-base systems that were known in principle but that had not vividly impressed potential users of the theory. In terms of his new exposition Sørensen evaluated those stable mixtures of acids and their salts that are called buffer mixtures and the zones of transformation of many indicators. Having systematized the indicator method of determining pH values Sørensen revealed something of its wide usefulness by resolving an old problem in enzyme chemistry, namely, the dependence of the activities of specific enzymes upon the degrees of acidity of the solutions. Here, then, in the classical paper "Études Enzymatiques," II (1909), supplemented by a more detailed mathematical analysis in 1912, was presented that rare combination of a vivid exposition of principles, exact quantitative data that