

UC Berkeley

College History

Title

Gilbert Newton Lewis, 1875-1946

Permalink

<https://escholarship.org/uc/item/1fv1978v>

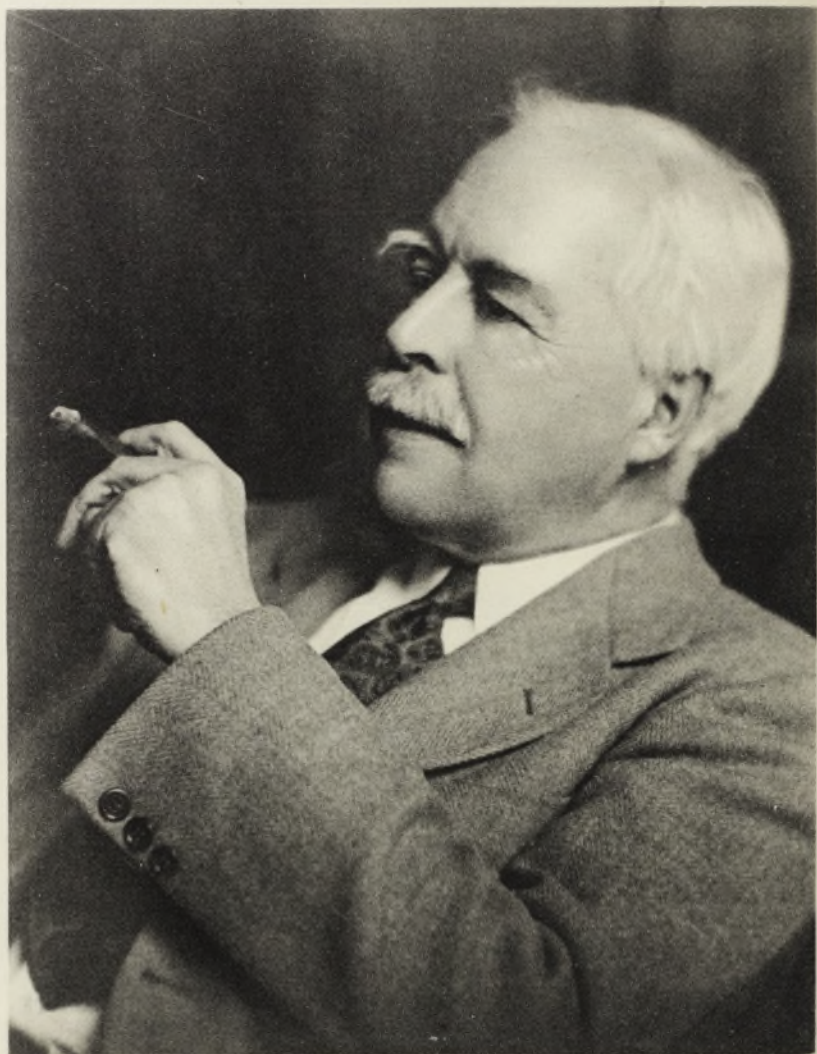
Author

Hildebrand, Joel H

Publication Date

1946

Peer reviewed



Gilbert N. Lewis

GILBERT NEWTON LEWIS

1875-1946

GILBERT NEWTON LEWIS was born near Boston, Massachusetts, on 25 October 1875. At the age of nine he was taken by his parents to live in Lincoln, Nebraska. Here, for several years, he had little formal schooling, enjoying an advantage which he mentioned in his later years as having occurred frequently in the careers of the world's most distinguished men, that of having 'escaped some of the ordinary processes of formal education'. At the age of thirteen he was admitted to the preparatory school of the University of Nebraska. He graduated from this school into the University of Nebraska, where he remained to complete the sophomore year. In 1893 he transferred to Harvard College, and, after graduating in 1896, spent a year in teaching at Phillips Academy at Andover. He then returned to Harvard for graduate work and received the degree of Master of Arts in 1898 and Doctor of Philosophy in 1899. His thesis was entitled, 'Some electrochemical and thermochemical relations of zinc and cadmium amalgams', and was published jointly with Theodore William Richards.

After remaining one year at Harvard as instructor, he went abroad on a travelling fellowship and spent a semester at Leipzig with Ostwald and another at Göttingen with Nernst. He returned to Harvard as instructor for three years, following which he accepted the position of Superintendent of Weights and Measures in the Philippine Islands and Chemist in the Bureau of Science at Manila. It was characteristic of his indefatigable pursuit of pure science that he found sufficient facilities and time, even there, to study the decomposition of silver oxide as well as to publish a paper on 'Hydration in solution'.

In 1905 he returned to the United States to join the notable group of physical chemists gathered at the Massachusetts Institute of Technology by A. A. Noyes; men who powerfully stimulated the development of physical chemistry in the United States. The seven years which he spent in that laboratory were marked by that intense scientific activity, both experimental and theoretical, which continued throughout his whole career. The results appeared in over thirty papers, several of which are particularly notable as laying the foundations for the later distinguished superstructures now well known to physical chemists throughout the world. They included a series of precise determinations of the electrode potentials of elements, contributions which he characterized in late years as high among those which had given him greatest satisfaction. It was during this period that he wrote his epoch-making papers, 'Outlines of a new system of thermodynamic chemistry', 1907, and 'The free energy of chemical substances', the nucleus from which grew a long series of papers on experimental determinations of free energies and, in 1923, his great work, written

with the assistance of Merle Randall, on 'Thermodynamics and the free energy of chemical substances'. But his was no mind that had to economize effort by concentrating it in any one or two directions, for during this same period, as a result of meeting Einstein, he became a prophet of and a contributor to the then unpopular theory of relativity, publishing papers on the subject with E. B. Wilson and later with E. C. Tolman.

By 1912 he had passed through the lower professorial grades and made such a reputation as to bring a call to become Dean of the College of Chemistry and Chairman of the Department of Chemistry at the University of California, an institution then rapidly rising under the able leadership of its president, Benjamin Ide Wheeler, to its present place among the most distinguished of American universities. Lewis accepted under wise stipulations, including new facilities for research and a complete departmental rejuvenation. He recruited a group of young men who, under his stimulating leadership established a centre of intense scientific activity. We were all simply instructors or professors of chemistry, not of its several subdivisions. No one was in a position to 'reserve' a field or to pose as the authority therein. There were no divisions within the department in either organization or spirit. All met together to discuss chemistry, organic, inorganic or physical, alike. The utmost freedom in discussion was the rule. The writer recalls one of the first research conferences which he attended when Lewis made a deliberately challenging statement, as he loved to do, taking a boyish delight in shocking conservative prejudice, whereupon a particularly brilliant graduate student interrupted with, 'No, that isn't so!' I was aghast at his temerity—such a remark at certain institutions would have landed the maker out on his ear; but Lewis turned to him with interest saying, 'No? Why not?' There followed a lively discussion, facts and logic alone determining the outcome.

The members of the department became like the Athenians who, according to the Apostle Paul, 'spent their time in nothing else, but either to tell or to hear some new thing'. Any one who thought he had a bright idea rushed to try it out on a colleague. Groups of two or more could be seen every day in offices, before blackboards or even in the corridors, arguing vehemently about these 'brain storms'. It is doubtful whether any paper ever emerged for publication that had not run the gauntlet of such criticism. The whole department thus became far greater than the sum of its individual members.

Lewis seemed to take as much satisfaction in the productivity of his young colleagues as in his own. He protected us from excessive teaching schedules. He sent new graduate students around to talk with the members of the staff, free to choose the particular problem which appealed most strongly. He accepted rather less than his share of research students; in striking contrast to the practice of certain other German-trained department heads who had imported the theory that all junior members of an 'institute' should work for its chief.

One of his first moves was to turn almost the entire staff loose upon the problem of starting the freshman in the way he should go, by fostering in him

in every conceivable way a scientific habit of mind. We met weekly to discuss the organization of the freshman course and the methods of presentation of difficult topics. Although the lectures were given to five hundred students at a time in the large chemistry auditorium, with great attention to lighting, projection and realization of the full dramatic possibilities of the subject, the laboratory and quizzing took place in sections of twenty-five, taught by a majority of the permanent staff with the help of numerous teaching assistants. The complaint that a freshman in a large university has no contact with professors has not applied in freshman chemistry at the University of California, for as many as eight full professors have in a single term taught freshman sections. The example thus set by senior professors has had a profound effect upon the apprentice teachers, making them take their teaching seriously and convincing them that talent for research is not demonstrated by indifferent teaching.

Lewis's own classroom teaching was limited to presiding at the weekly 'research conference' of the whole department, but there his influence was impressive, upon staff and students alike. It was a rare presentation that did not elicit some stimulating question or comment from his far-ranging knowledge and interest. To-day, there hangs on the wall of the seminar room, near the chair in which he sat, the portrait reproduced herewith, showing him in his characteristic pose and with his ever-present cigar.

The remainder of the undergraduate curriculum in chemistry was limited, under his leadership, to a small number of basic courses, with great freedom of election during the junior and senior years. The contrast in this respect with certain other departments of the university has been so great as to suggest to the writer an empirical academic law to the effect that the number of courses taught by a department varies inversely with the eminence of its faculty and with the advancement of knowledge in the field.

The methods adopted for graduate instruction were such as to emphasize research. In place of lectures repeating material already available in book form, there were seminars on topics in process of being worked up for publication. A notable illustration is furnished by a seminar on valence offered by Lewis himself which culminated in the publication in 1923 of his influential book, *Valence and the structure of atoms and molecules*. The foreword to the book contains his own generous testimony to the co-operative nature of practically all the output of the laboratory, which, under his influence, has prevailed over the years against all the temptations of human selfishness and jealousy. 'To my colleagues and students of the University of California, without whose help this book would not have been written. In our many years of discussion of the problems of atomic and molecular structure, some of the ideas here presented have sprung from the group rather than from an individual; so that in a sense I am acting only as editor for this group.'

In conducting the affairs of the Department of Chemistry, the business unit, as well as of the College of Chemistry, the curricular unit, Lewis showed himself to be one of the all too rare leaders who are able to influence the members

of their organizations by natural gifts of reason and persuasion and do not need to invoke the artificial aids of authority and position. Despite a minimum of formal parliamentary procedure, whose tricks, as all know, may be used to thwart true democracy, there was always the fullest consultation with interested members of the department before important steps were taken. The result was a high degree of co-operation and loyalty. These members have never been factious and even the wives get along splendidly with each other.

The influence of Lewis was exerted upon the university as well as upon his own department. He came to it in the period during which the university was growing from adolescence to maturity, and which was naturally a period of 'Sturm und Drang'. From it has emerged a great university almost unique in the extent to which its faculty share in determining policies. A recent staff writer in *Fortune* magazine has referred to its Academic Senate as 'undoubtedly the most self-determined faculty group in the country, and certainly the most conspicuous contribution of the University to educational administration'. Lewis was outstanding during these years among the men who had the dignity, the insistence, and the sense of responsibility which made the building of a great institution the common devoted enterprise of its administration and faculty.

His work at California was interrupted by World War I. In December of 1917 he was commissioned a Major in the Gas Service, later the Chemical Warfare Service, and in January 1918, went to France. He began as Director of the Chemical Warfare Service Laboratory in Paris, but having been sent to the front as an observer during the great German offensive in March, he made upon his return, such a penetrating report to the Chief, General Amos A. Fries, that the latter made him Chief of the Defence Division of the Chemical Warfare Service. In this capacity he organized the American Expeditionary Force Gas Defence School and established it near the A.E.F. Headquarters at Chaumont, at Hanlon Field, the Experimental Field of the service. Before long, the school was training as many as two-hundred gas officers a week for the American Army, and as a result, gas casualties, which early in 1918, had constituted the majority of all casualties, soon dropped to a very small percentage of the total. The Distinguished Service Medal, awarded to him in 1922, was accompanied by the following citation: 'By his unusual energy, marked ability, and high technical attainments he rendered extremely valuable service by securing first-hand data on the uses and effects of gas and submitting reports of such value that they became fundamentals upon which the gas-warfare policies of the American Expeditionary Forces were thereafter largely based. Later, as chief of the defence division, Chemical Warfare Service, he obtained a high state of efficiency in the protection of our officers and soldiers against enemy gas and furthered the successes of American arms by securing a better and more effective use of gas, especially mustard gas, against the enemy, thereby rendering services of great value to our Government.'

He returned to Washington shortly before the end of the war, where he was promoted to the rank of Lieutenant-Colonel and made Chief of the Training

Division of the Chemical Warfare Service. He was awarded also the Cross of the Legion of Honour.

Returning to the University of California, he began working, with the assistance of Dr Merle Randall, upon his great treatise on thermodynamics, referred to above. This was published in 1923. It represented the fruition of work begun in 1899 and presented in a series of sixty papers.

It had long been the aim of chemists to possess tables of chemical affinity which would make it possible to predict the direction of any chemical reaction. The extensive determinations of heats of reaction made during the latter half of the last century had this aim largely in view. It was thought at one time that the heat of a reaction could be taken as the measure of chemical affinity, and consequently that the heats of formation of the substances involved could serve for the prediction of the direction of a reaction. The development of thermodynamics showed, however, that the correct measure of chemical affinity is not heat but 'free energy'. Lewis set for himself many years ago the task of preparing tables of free energy to serve this purpose. The accomplishment of this task involved, first, the critical examination, and in many cases the recalculation, of a wide range of chemical data. However, since the data at hand were not obtained with any such systematic aim in view as that proposed by Lewis, it became necessary for him and his co-workers to measure a large number of chemical equilibria, and to study the electromotive force of many cells. The task involved, further, the application of thermodynamics to solutions, a field in which, before his work, comparatively little progress had been made.

The book summarized the work of twenty-five years. It contained the free energies of 143 important substances, making possible the calculation of chemical equilibria for many hundreds of reactions. The importance of these data is illustrated by the following remark of a reviewer: 'If this book can further the use of those (free energy) values and can create a demand for more data, it will have added more to the development of civilization and the increase of human comfort than any other chemical treatise in all history'.

In addition to these exceedingly important data, the book contains a large number of original and important applications of thermodynamics to chemical problems. In the words of another reviewer, published in *Nature*: 'For many years back the published researches of G. N. Lewis and his collaborators have occupied a prominent place in the branch of science dealing with the application of thermodynamics to the solution of chemical problems. The book now under review, of which he and his co-worker, Merle Randall, are joint authors, collects and summarizes these researches and places them in position in the general framework of thermodynamics. For this alone all interested in matters pertaining to physico-chemical theory would owe them thanks, but the debt is increased by the fact that no better account of modern chemical thermodynamics than appears in this book can be placed in the hands of advanced students.'

Lewis developed a variety of special methods, chemical, algebraic, arithmetical and graphical, for the treatment of thermodynamic data. These methods

did much to rescue thermodynamics from a barren position in treatises on theoretical physics, and to place it as working tool of extraordinary potency in the hands of the chemist, who had been up to that time, far too ignorant of its vital importance to him.

Lewis's first paper pertaining to thermodynamics was a joint paper with T. W. Richards, entitled 'Some electrochemical and thermochemical relations of zinc and cadmium amalgams', embodying the results of his doctor's thesis. This was followed the next year by a most important paper in which he investigated the integration constant of the free energy equation. In 1906 he definitely established by equilibrium measurements the value of the oxygen electrode, and showed that the direct measurements of the potential did not give the equilibrium value. This was the beginning of the long series of experimental and theoretical investigations to bring the various physico-chemical methods into agreement. The most important theoretical paper during this period was the 'Outline of a new system of thermodynamic chemistry'. He then began a determination of the electrode potentials of a number of elements, including lithium, sodium, potassium, rubidium, chlorine, bromine, iodine, oxygen, mercury, silver, thallium, lead and iron. All these measurements were carried out with a precision far beyond that of the previous investigators. The ingenuity shown in obtaining the values for the alkali metal electrodes is worthy of particular mention. In 1912, he laid the foundations for the exact treatment of aqueous solutions with the calculation of the activities of the ions of strong electrolytes.

With Burrows, 1912, he reversibly synthesized urea. It is noteworthy that the first typically organic substance to be synthesized from inorganic materials was likewise the first to be reversibly synthesized from the elements. In 1917, with Gibson, he began his investigation into the scope of the third law of thermodynamics, a return to the problem discussed in his doctor's thesis. In 1921, with Randall, he laid the basis for the treatment of concentrated solutions, and freed chemists from the necessity of limiting their work to dilute solutions; in the same year, in the paper on 'Activity coefficient of strong electrolytes', again with Randall, he treated comprehensively the various methods of measuring the colligative properties of solutions. This paper also enunciated the important principle of the ionic strength, which has since been developed theoretically by Debye and Huckel.

No less important than the contributions of Lewis to thermodynamics have been his theories of valence. His first contribution upon this subject, entitled 'The atom and the molecule' appeared in 1916 in the *Journal of the American Chemical Society*, almost simultaneously with the paper by Kossel in the *Annalen der Physik*, which dealt with the same general subject. Later publications by Lewis appeared in the *Proceedings of the National Academy of Science* and in the *Transactions of the Faraday Society*. His most extensive treatment of the topic appeared in 1923 in a volume entitled *Valence and the structure of atoms and molecules*, published as a *Monograph of the American Chemical Society*. In these publications he elaborated, as did Kossel, the ideas of Abegg regarding

the significance of an outer octet of electrons of an atom, but he went farther than Kossel in calling attention to evidence indicating the pairing of electrons, and gave an explanation thereby of the non-polar type of chemical bonds. The organic and inorganic views regarding the chemical bond, which had, prior to this time, little in common, were reconciled by this concept of Lewis. He further harmonized with electron structure the empirical generalizations of Werner concerning valence and co-ordination number. He called attention to the atoms of 'variable kernel', since recognized by physicists from spectroscopic studies. He pointed out the peculiar properties of molecules having an odd number of electrons and drew attention to relations between magnetic properties and electron structure.

These theories have had a wide influence upon chemical thought. One may mention, especially, their fruitful application in a series of papers by Langmuir, in the *Journal of the American Chemical Society*. Langmuir had previously stated that 'the theory of valence recently advanced by G. N. Lewis seems to offer by far the most satisfactory picture of the mechanism of chemical combination that has yet been suggested'. Present day chemical literature abounds in references to this work of Lewis. For some time his views upon the nature of the chemical bond, particularly the paired electron bond, were not popular among physicists, because they bore no very close relationship to the Bohr atom, but the advent of the new quantum mechanics yielded a striking confirmation of this type of bond, and gained a new appreciation of the significance of the views of Lewis. Pauling stated that 'the application of the quantum mechanics to the interaction of more complicated atoms, and to the non-polar chemical bond, in general, is now being made. . . . It is worthy of mention that qualitative conclusions have been drawn which are completely equivalent to G. N. Lewis's theory of the shared electron pair.'

Certain additional lines of research by Lewis deserve particular mention in these pages. In 1933 he devoted great energy to the isolation of deuterium, which had just been discovered by H. C. Urey, who received his doctoral degree in the Berkeley department. With the assistance of a number of young collaborators, he determined by ingenious micro-methods a number of the properties of the element itself, of 'heavy water', and of other deuterium compounds, and he supplied E. O. Lawrence and other leading physicists with the deuterium oxide with which most of the first determinations of the physical properties of deuterium were obtained. A visiting scientist asked him one day what he was doing with a piece of apparatus provided with a long cellophane osmotic tube; he replied with one of those flashes of his ready wit for which he was renowned among his friends, 'I am trying to make heavy water with an artificial bladder'.

In his *Valence*, in 1923, Lewis had outlined the several possible definitions of acid base systems, adding his own and most general definition of all, that 'a basic substance is one which has a lone pair of electrons which may be used to complete the stable group of another atom, and that an acid substance is one which can employ a lone pair from another molecule in completing the

stable group of one of its own atoms. In other words, the basic substance furnishes a pair of electrons for a chemical bond, the acid substance accepts such a pair'. This definition not only divorced the concept of a base from the properties of hydroxyl ion, as did the Lowry-Brönsted definition later, but also freed the notion of acid from the limitation that it must be able to 'donate' a proton. The Lewis point of view was largely overlooked during the 1930's in the wave of enthusiasm for the proton-donor-acceptor theory as the 'modern' and 'correct' one, to be taught as such, even in elementary courses. Lewis returned to this question in a paper published in 1938 in the *Journal of the Franklin Institute*, entitled, 'Acids and bases'. In it he wrote, 'The recognition of Brönsted and his school of such ions as the halide ions and acetate ion as true bases, together with the development of the concept of organic bases, tends to make the present recognized list of bases identical with my own. On the other hand, any similar valuable and instructive extension of the idea of acids has been prevented by what I am tempted to call the modern cult of the proton. To restrict the group of acids to those substances which contain hydrogen interferes as seriously with the systematic understanding of chemistry as would the restriction of the term oxidizing agent to substances containing oxygen.'

He then proceeded to give a number of instances of essentially acid-base reactions, including typical changes in the colours of indicators, where no proton transfer could possibly be involved, as where such bases as pyridine or triethylamine react with such acids as SO_2 , BCl_3 or SnCl_4 in solvents such as dioxane or CCl_4 . These experiments have helped to bring the enthusiasts for the proton theory down to earth, and to realize that any such system represents convenience to the particular purpose at hand rather than ultimate truth. The fact that the organic chemist finds the proton-donor-accepter system appropriate for most of his studies should not be used to set up a system of instruction in chemistry which would deny the right of, say the geo-chemist to speak of acidic and basic oxides, lavas or rocks.

Lewis had always taken great interest in colour. Indeed, he used it in 1920 as the subject of his Faculty Research Lecture, an honour annually bestowed by the Academic Senate of the University upon one of its members. During his later years he returned to a study of colour and fluorescence in relation to structure, publishing with his collaborators a series of eighteen papers. In this work, as always before, he exhibited his wide grasp of organic chemistry, a fact insufficiently appreciated by those who have thought of him primarily as a physical chemist.

Few men in their sixties have the imagination to branch out in new directions. It was characteristic of Lewis that most of the above new work was done after the age of 65, at which time, according to University rules, he laid down his administrative functions while continuing as a professor till the age of retirement at 70. But Lewis, not content with occupying his mind with fluorescence and phosphorescence was also then reading extensively for recreation in the field of American pre-history and in 1945, read to the Chit-Chat Club of San Francisco a daring paper which is to be published in an anthropological journal.

Another paper on 'The thermodynamics of glaciation' appeared posthumously in *Science*. The mental activity which thus caused him to range from time to time beyond the bounds of his main field of research had been exhibited earlier in two articles on price stabilization, 'Europas Skulder och Mynfoten', *Finsk Tidskrift*, 1924, and 'A plan for stabilizing prices', *The Economic Journal*, 1925.

This far-ranging quality of mind, together with his sparkling sense of humour, made him one of the most stimulating and charming of companions and conversationalists. He loved good company and always made it better by joining it. He was very sensitive to humbug or pretence. He shunned the crowd and squirmed under personal praise. A number of his friends and former students desiring to honour him by a dinner, knowing his tastes, avoided the set laudatory speeches under which a lesser man would have beamed, and simply had a rather hilarious time together, all remarks being shouted by those who felt the urge to do so.

Lewis was not at ease in speaking in public and rarely accepted invitations to deliver any but a scientific address. When sufficiently aroused, however, he could be effective in debate, and few cared to cross swords with him in those early arguments in the Academic Senate. It was with the pen that he chiefly showed literary skill. Those who have followed his writings have often been arrested by passages of rare quality. The preface to *Thermodynamics* contains the following sample: 'There are ancient cathedrals which, apart from their consecrated purpose, inspire solemnity and awe. Even the curious visitor speaks of serious things, with hushed voice, and as each whisper reverberates through the vaulted nave, the returning echo seems to bear a message of mystery. The labor of generations of architects and artisans has been forgotten, the scaffolding erected for their toil has long since been removed, their mistakes have been erased, or have become hidden by the dust of centuries. Seeing only the perfection of the completed whole, we are impressed as by some super-human agency. But sometimes we enter such an edifice that is still partly under construction; then the sound of hammers, the reek of tobacco, the trivial jests bandied from workman to workman, enable us to realize that these great structures are but the result of giving to ordinary human effort a direction and purpose.'

'Science has its cathedrals, built by the efforts of a few architects and of many workers.'

Many honours came to him. He received honorary degrees from the Universities of Chicago, Liverpool, Madrid, Pennsylvania and Wisconsin. He was elected to honorary membership in the Royal Institution of Great Britain, the Chemical Society of London, the Indian Academy of Sciences, the Swedish Academy, the Danish Academy, the Royal Society and the Franklin Institute of Pennsylvania. He was awarded the Nichols, Gibbs, Davy, Arrhenius, Richards and Society of Arts and Sciences Medals. He was Silliman Lecturer at Yale in 1925, choosing as his topic, 'The anatomy of science' and doing his best to shock scientific prejudices in several fields.

The end came to him suddenly on 23 March 1946 and, appropriately, in

the laboratory while continuing his experiments on fluorescence. He is survived by his widow, Mary Sheldon Lewis, to whom he was married in 1912 and by his two sons, Richard Newton and Edward Sheldon, both chemists, and his daughter, Margery Selby.

'The half century which terminated with the death of Gilbert Newton Lewis will always be regarded as one of the most brilliant in the history of scientific discovery, and his name ranks among the highest in the roster of those that made it great. The electron theory of chemical valence, the advance of chemical thermodynamics, the separation of isotopes which made possible the use of the deuteron in the artificial transmutation of the elements, the unravelling of the complex phenomena of the adsorption, fluorescence and phosphorescence of the organic dyes are among the achievements which will ever be associated with his name.

'The methods he chose were always simple and to the point. He was impatient of unnecessary elaboration, and like Sir Humphrey Davy, who was one of his heroes, loved to make important discoveries with a few test-tubes and simple chemicals. When the point at issue seemed to him sufficiently important, he would not hesitate to employ apparatus requiring skill and delicacy of manipulation, as in the beautiful but difficult experiment by which he and Calvin demonstrated the paramagnetism of the phosphorescent triplet state.

'He was ever conscious of the necessity for economy of time in research and out of the wealth of his ideas was careful to select those that would lead swiftly to the goal.

'As a man he was a great soul whose inspiration will never be forgotten by those who knew and loved him. He was one of those rare scientists, like J. J. Thomson and Rutherford, who are also great teachers and leaders of a school, so that their influence is multiplied by the many they have inspired.

'His brain was still fertile of ideas and his faculties all but unimpaired until the very end, when he died suddenly of heart failure, in harness as he would have wished it, in the act of performing his last experiment.'¹

JOEL H. HILDEBRAND

BIBLIOGRAPHY

- 1898-1899. (With T. W. RICHARDS.) Some electrochemical and thermochemical relations of zinc and cadmium amalgams. *Proc. Amer. Acad.* **34**, 87; *Z. phys. Chem.* **28**, 1.
- 1899-1900. The development and application of a general equation for free energy and physico-chemical equilibrium. *Proc. Amer. Acad.* **35**, 3; *Z. phys. Chem.* **32**, 364.
1900. A new conception of thermal pressure and a theory of solutions. *Proc. Amer. Acad.* **36**, 145; *Z. phys. Chem.* **35**, 343.
1901. The law of physico-chemical change. *Proc. Amer. Acad.* **37**, 49; *Z. phys. Chem.* **38**, 205.
1905. The autocatalytic decomposition of silver oxide. *Bull. Goy. Lab. Manila, P.I.* **30**; *Proc. Amer. Acad.* **40**, 719; *Z. phys. Chem.* **52**, 310.

¹ Quoted from the resolution prepared by Professor G. E. Gibson for the Academic Senate of the University of California.

1905. Hydration in solution. *Bull. Gov. Lab. Manila, P.I.* 30; *Z. phys. Chem.* 52, 224.
1906. Concerning silver oxide and silver suboxide. *J. Amer. Chem. Soc.* 28, 139; *Philippine Jour. Sci.* 1, 439; *Z. phys. Chem.* 55, 449.
1906. The potential of the oxygen electrode. *J. Amer. Chem. Soc.* 28, 158; *Z. phys. Chem.* 55, 465.
1906. (With R. F. JACKSON.) Galvanic polarization on a mercury cathode. *Proc. Amer. Acad.* 41, 399; *Z. phys. Chem.* 56, 193.
1906. (With P. WHEELER.) The electrical conductivity of solutions in liquid iodine. *Proc. Amer. Acad.* 41, 419; *Z. phys. Chem.* 56, 179.
1906. Über Komplexbildung. Hydratation und Farbe. *Z. phys. Chem.* 56, 223.
1906. An elementary proof of the relation between the vapour pressures and the composition of a binary mixture. *J. Amer. Chem. Soc.* 28, 569.
1906. On the applicability of Raoult's laws to molecular weight determinations in mixed solvents and in simple solvents whose vapour dissociates. *J. Amer. Chem. Soc.* 28, 766.
1906. A review of recent progress in physical chemistry. *J. Amer. Chem. Soc.* 28, 893.
1906. Equilibrium in the Deacon process. *J. Amer. Chem. Soc.* 28, 1380.
1907. The specific heat of solids at constant volume and the law of Dulong and Petit. *J. Amer. Chem. Soc.* 29, 1165; *Z. anorg. Chem.* 55, 200.
1907. Outlines of a new system of thermodynamic chemistry. *Proc. Amer. Acad.* 43, 259; *Z. phys. Chem.* 61, 129.
1908. The osmotic pressure of concentrated solutions and the laws of the perfect solution. *J. Amer. Chem. Soc.* 30, 668; *Chem. News*, 99, 40.
1908. The determination of ionic hydration from electromotive force. *J. Amer. Chem. Soc.* 30, 1355; *Z. Electrochem.* 14, 509.
1908. A revision of the fundamental laws of matter and energy. *Technol. Quart.* 21, 212; *Phil. Mag.* 16, 705; *Ann. Naturphil.* 7, 429.
1908. The ionic theory. *Sch. Sci. Math.* 8, no. 6, 484.
1909. (With L. W. SARGENT.) The potential of the ferro-ferricyanide electrode. *J. Amer. Chem. Soc.* 31, 355.
1909. (With L. W. SARGENT.) Potentials between liquids. *J. Amer. Chem. Soc.* 31, 363.
1909. (With R. C. TOLMAN.) The principle of relativity and non-Newtonian mechanics. *Proc. Amer. Acad.* 44, 711; *Phil. Mag.* 18, 510.
1909. The fundamental laws of matter and energy. *Science*, 30, 84.
1909. The use and abuse of the ionic theory. *Z. phys. Chem.* 70, 212; *Science*, 30, 1.
1910. (With C. L. VON ENDE.) The potential of the thallium electrode. *J. Amer. Chem. Soc.* 32, 732.
1910. The theory of the determination of transference numbers by the method of moving boundaries. *J. Amer. Chem. Soc.* 32, 862.
1910. On four dimensional-vector analysis and its application in electrical theory. *Proc. Amer. Acad.* 46, 165; *Jb. Radioakt.* 7, 329.
1910. (With C. A. KRAUS.) The potential of the sodium electrode. *J. Amer. Chem. Soc.* 32, 1459.
1911. (With A. EDGAR.) The equilibrium between nitric acid, nitrous acid and nitric oxide. *J. Amer. Chem. Soc.* 33, 292.
1911. (With F. R. RUPERT.) The potential of the chlorine electrode. *J. Amer. Chem. Soc.* 33, 299.
1911. (With M. RANDALL.) The heat content of the various forms of sulphur. *J. Amer. Chem. Soc.* 33, 476.
1912. (With F. G. KEYES.) The potential of the potassium electrode. *J. Amer. Chem. Soc.* 34, 119.
1912. (With G. H. BURROWS.) The equilibrium between ammonium carbonate and ammonium carbamate in aqueous solution at 25°. *J. Amer. Chem. Soc.* 34, 993.
1912. (With M. RANDALL.) A summary of the specific heats of gases. *J. Amer. Chem. Soc.* 34, 1128.

1912. (With G. H. BURROWS.) The free energy of organic compounds. I. The reversible synthesis of urea and of ammonium cyanate. *J. Amer. Chem. Soc.* **34**, 1515.
1912. (With E. B. WILSON.) The space-time manifold of relativity; The non-euclidean geometry of mechanics and electromagnetics. *Proc. Amer. Acad.* **48**, 389.
1912. The activity of the ions and the degree of dissociation of strong electrolytes. *J. Amer. Chem. Soc.* **34**, 1631.
1913. The free energy of chemical substances. *J. Amer. Chem. Soc.* **35**, 1.
1913. (With F. G. KEYES.) The potential of the lithium electrode. *J. Amer. Chem. Soc.* **35**, 340.
1913. Valence and tautomerism. *J. Amer. Chem. Soc.* **35**, 1448.
1914. (With E. Q. ADAMS.) Notes on quantum theory: a theory of ultimate rational units; numerical relations between elementary charge, wirkungsquantum, constant of Stefan's law. *Phys. Rev.* **3**, 92.
1914. (With W. N. LACEY.) The potential of the copper electrode and the activity of bi-valent ions. *J. Amer. Chem. Soc.* **36**, 804.
1914. (With E. Q. ADAMS.) Notes on quantum theory. The distribution of thermal energy. *Phys. Rev.* **4**, 331.
1914. (With M. RANDALL.) The free energy of oxygen, hydrogen and the oxides of hydrogen. *J. Amer. Chem. Soc.* **36**, 1969.
1914. (With M. RANDALL.) The free energy of iodine compounds. *J. Amer. Chem. Soc.* **36**, 2259.
1914. (With M. RANDALL.) The free energy of the various forms of elementary sulphur. *J. Amer. Chem. Soc.* **36**, 2468.
1915. (With M. RANDALL.) The free energy of some carbon compounds. *J. Amer. Chem. Soc.* **37**, 458.
1915. (With E. Q. ADAMS.) The Maxwell distribution law in Newtonian and non-Newtonian mechanics. *Phys. Rev.* **5**, 510.
1915. (With W. N. LACEY.) The equilibrium between carbon oxysulphide, carbon monoxide and sulphur. *J. Amer. Chem. Soc.* **37**, 1976.
1915. (With W. L. ARGO.) The potential of the rubidium electrode. *J. Amer. Chem. Soc.* **37**, 1983.
1915. (With E. Q. ADAMS.) The free energy of nitrogen compounds. *J. Amer. Chem. Soc.* **37**, 2308.
1915. (With E. Q. ADAMS and E. H. LANMAN.) Electrical transference in amalgams. *J. Amer. Chem. Soc.* **37**, 2656.
1916. The atom and the molecule. *J. Amer. Chem. Soc.* **38**, 762.
1916. Steric hindrance and the existence of odd molecules (free radicals). *Proc. Nat. Acad. Sci.* **2**, 586.
1916. (With M. RANDALL.) The free energy of bromine compounds. *J. Amer. Chem. Soc.* **38**, 2348.
1916. (With T. B. HINE.) Electrical conduction in dilute amalgams. *Proc. Nat. Acad. Sci.* **2**, 634.
1917. (With T. B. BRIGHTON.) The potential of the lead electrode. *J. Amer. Chem. Soc.* **39**, 1906.
1917. The static atom. *Science*, **46**, 297.
1917. (With T. B. BRIGHTON and R. L. SEBASTIAN.) A study of hydrogen and calomel electrodes. *J. Amer. Chem. Soc.* **39**, 2245.
1917. (With HYMAN STORCH.) The potential of the bromine electrode; the free energy of dilution of hydrogen bromide; the distribution of bromide between several phases. *J. Amer. Chem. Soc.* **39**, 2544.
1917. (With G. E. GIBSON.) The entropy of the elements and the third law of thermodynamics. *J. Amer. Chem. Soc.* **39**, 2554.
1918. (With M. RANDALL and F. R. v. BICHOWSKY.) A preliminary study of reversible reactions of sulphur compounds. *J. Amer. Chem. Soc.* **40**, 356.

1918. (With M. RANDALL.) Equilibrium in the reaction between water and sulphur at the boiling point of sulphur. *J. Amer. Chem. Soc.* **40**, 362.
1918. (With E. D. EASTMAN and W. H. RODEBUSH.) The heat capacity of electro-positive metals and the thermal energy of free electrons. *Proc. Nat. Acad. Sci.* **4**, 25.
1918. (With D. B. KEYES.) Equilibria involving cyanogen iodide; the free energy of formation of cyanogen. *J. Amer. Chem. Soc.* **40**, 472.
1918. (With T. B. BRIGHTON.) The oxidizing power of cyanates and the free energy of formation of cyanides. *J. Amer. Chem. Soc.* **40**, 482.
1919. (With G. A. LINHART.) The degree of ionization of very dilute electrolytes. *J. Amer. Chem. Soc.* **41**, 1951.
1920. (With G. E. GIBSON.) The third law of thermodynamics and the entropy of solutions and of liquids. *J. Amer. Chem. Soc.* **42**, 1529.
1921. (With M. RANDALL.) The thermodynamic treatment of concentrated solutions and applications to thallium amalgams. *J. Amer. Chem. Soc.* **43**, 233.
1921. Colour and chemical constitution. *Chem. Metall. Engrg.* **24**, 871.
1921. (With M. RANDALL.) The activity coefficient of strong electrolytes. *J. Amer. Chem. Soc.* **43**, 1112.
1922. (With G. E. GIBSON and W. M. LATIMER.) A revision of the entropies of the elements. *J. Amer. Chem. Soc.* **44**, 1008.
1922. The chemistry of the stars and the evolution of radioactive substances. *Publ. Astron. Soc. Pacific*, **34**, 309.
- 1922-1923. Physical constants and the ultimate rational units. *Contrib. Jefferson Phys. Lab.* **15**, no. 21; *Phil. Mag.* **45**, 266.
1923. (With M. RANDALL.) *Thermodynamics and the free energy of chemical substances*. McGraw-Hill, New York.
1923. *Valence and the structure of atoms and molecules*. The Chemical Catalogue Company, New York.
1923. Valence and the electrons. *Trans. Faraday Soc.* **19**, 452.
1923. Extremely dry liquids. *J. Amer. Chem. Soc.* **45**, 2836.
1924. The magnetochemical theory. *Chem. Rev.* **1**, 233.
1924. The magnetism of oxygen and the molecule O_4 . *J. Amer. Chem. Soc.* **46**, 2027.
1924. Europas Skudder och Mynfoten. *Finsk Tidskrift*, December.
1925. A new principle of equilibrium. *Proc. Nat. Acad. Sci.* **11**, 179.
1925. A plan for stabilising prices. *The Econ. J.* **35**, 40.
1925. Ultimate rational units and dimensional theory. *Phil. Mag.* **49**, 739.
1925. (With D. F. SMITH.) The theory of reaction rate. *J. Amer. Chem. Soc.* **47**, 1508.
1925. The distribution of energy in thermal radiation and the law of entire equilibrium. *Proc. Nat. Acad. Sci.* **11**, 422.
1925. (With N. W. TAYLOR.) The paramagnetism of 'odd molecules'. *Proc. Nat. Acad. Sci.* **11**, 456.
1926. The nature of light. *Proc. Nat. Acad. Sci.* **12**, 22.
1926. Light waves and light corpuscles. *Nature, Lond.* **117**, 236.
1926. The path of light quanta in an interference field. *Proc. Nat. Acad. Sci.* **12**, 439.
1926. *The anatomy of science*. Yale University Press, New Haven.
1926. The conservation of photons. *Nature, Lond.* **118**, 874.
1927. The entropy of radiation. *Proc. Nat. Acad. Sci.* **13**, 307.
1927. A new equation for the distribution of radiant energy. *Proc. Nat. Acad. Sci.* **13**, 471.
1927. A disproof of the radiation theory of chemical activation. *Proc. Nat. Acad. Sci.* **13**, 623.
1927. Entropy at infinite pressure and the equation of state of solids. *Z. phys. Chem.* (Cohen-Festband), **130**, 532.
1928. (With A. R. OLSON.) Natural radioactivity and the origin of species. *Nature, Lond.* **121**, 673.

1928. (With J. E. MAYER.) Thermodynamics based on statistics. I. *Proc. Nat. Acad. Sci.* **14**, 569.
1928. (With J. E. MAYER.) Thermodynamics based on statistics. II. *Proc. Nat. Acad. Sci.* **14**, 575.
1929. (With J. E. MAYER.) The quantum laws and the uncertainty principle of Heisenberg. *Proc. Nat. Acad. Sci.* **15**, 2.
1929. (With J. E. MAYER.) The thermodynamics of gases which show degeneracy (Entartung). *Proc. Nat. Acad. Sci.* **15**, 208.
1930. The symmetry of time in physics. *Science*, **71**, 569.
1930. Quantum kinetics and the Planck equation. *Phys. Rev.* **35**, 1533.
1930. The principle of identity and the exclusion of quantum states. *Phys. Rev.* **36**, 1144.
1931. Generalized thermodynamics including the theory of fluctuations. *J. Amer. Chem. Soc.* **53**, 2578.
1931. A more fundamental thermodynamics. *Phys. Rev.* **38**, 376.
1933. The chemical bond. *J. Chem. Phys.* **1**, 17.
1933. The isotope of hydrogen. *J. Amer. Chem. Soc.* **55**, 1297.
1933. (With R. T. MACDONALD.) Concentration of H² isotope. *J. Chem. Phys.* **1**, 341.
1933. (With R. E. CORNISH.) Separation of the isotopic forms of water by fractional distillation. *J. Amer. Chem. Soc.* **55**, 2616.
1933. (With M. F. ASHLEY.) Spin of hydrogen isotope. *Phys. Rev.* **43**, 837.
1933. (With F. H. SPEDDING.) A spectroscopic search for H³ in concentrated H². *Phys. Rev.* **43**, 964.
1933. (With M. S. LIVINGSTON and E. O. LAWRENCE.) The emission of alpha-particles from various targets bombarded by deuterons of high speed. *Phys. Rev.* **44**, 55.
1933. (With E. O. LAWRENCE and M. S. LIVINGSTON.) The emission of protons from various targets bombarded by deuterons of high speed. *Phys. Rev.* **44**, 56.
1933. (With R. T. MACDONALD.) Some properties of pure H²H²O. *J. Amer. Chem. Soc.* **55**, 3057.
1933. A simple type of isotopic reaction. *J. Amer. Chem. Soc.* **55**, 3502.
1933. The biochemistry of water containing hydrogen isotope. *J. Amer. Chem. Soc.* **55**, 3503.
1933. (With T. C. DOODY.) The mobility of ions in H²H²O. *J. Amer. Chem. Soc.* **55**, 3504.
1933. (With R. T. MACDONALD.) The viscosity of H²H²O. *J. Amer. Chem. Soc.* **55**, 4730.
1933. (With A. R. OLSON and W. MARONEY.) The dielectric constant of H²H²O. *J. Amer. Chem. Soc.* **55**, 4731.
1933. (With D. B. LUTEN.) The refractive index of H₂O¹⁸, and the complete isotopic analysis of water. *J. Amer. Chem. Soc.* **55**, 5061.
1934. The biology of heavy water. *Sci.* **79**, 151.
1934. (With M. S. LIVINGSTON, M. C. HENDERSON and E. O. LAWRENCE.) The disintegration of deuterons by high speed protons and the instability of the deuteron. *Phys. Rev.* **45**, 242.
1934. (With P. W. SCHUTZ.) Some properties of pure deutacetic acid. *J. Amer. Chem. Soc.* **56**, 493.
1934. (With R. T. MACDONALD and P. W. SCHUTZ.) The vapour pressure of liquid and solid deutochloric acid. *J. Amer. Chem. Soc.* **56**, 494.
1934. (With W. T. HANSON.) The vapour pressure of mixtures of light and heavy hydrogen. *J. Amer. Chem. Soc.* **56**, 1000.
1934. (With W. T. HANSON.) The vapour pressure of solid and liquid heavy hydrogen. *J. Amer. Chem. Soc.* **56**, 1001.
1934. (With P. W. SCHUTZ.) The vapour pressure of liquid and solid deutocyanic acid. *J. Amer. Chem. Soc.* **56**, 1002.
1934. (With P. W. SCHUTZ.) The ionization constant of deutacetic acid. *J. Amer. Chem. Soc.* **56**, 1002.

1934. (With M. S. LIVINGSTON, M. C. HENDERSON and E. O. LAWRENCE.) On the hypothesis of the instability of the deuteron. *Phys. Rev.* **45**, 497.
1934. Different kinds of water. *IX. Congr. Int. Quimica*, Madrid, April.
1934. (With W. T. HANSON.) The vapour pressure of solid and liquid deuterium and the heats of sublimation of fusion and of vaporization. *J. Amer. Chem. Soc.* **56**, 1687.
1934. (With P. W. SCHUTZ.) The ionization of some weak electrolytes in heavy water. *J. Amer. Chem. Soc.* **56**, 1913.
1934. The genesis of the elements. *Phys. Rev.* **46**, 897.
1936. A theory of orbital neutrons. *Phys. Rev.* **50**, 857.
1936. (With R. T. MACDONALD.) The separation of lithium isotopes. *J. Amer. Chem. Soc.* **58**, 2519.
1937. (With P. W. SCHUTZ.) Refraction of neutrons. *Phys. Rev.* **51**, 369.
1937. Neutron optics. *Phys. Rev.* **51**, 371.
1937. (With P. W. SCHUTZ.) Neutron refraction. *Phys. Rev.* **51**, 1105.
1937. Review of 'A commentary on the scientific writings of J. Willard Gibbs' (edited by F. G. Donnan and Arthur Haas). *J. Amer. Chem. Soc.* **59**, 2749.
1938. Acids and bases. *J. Franklin Inst.* **226**, 293.
1939. (With G. T. SEABORG.) Primary and secondary acids and bases. *J. Amer. Chem. Soc.* **61**, 1886.
1939. (With G. T. SEABORG.) Trinitrotriphenylmethide ion as a secondary and primary base. *J. Amer. Chem. Soc.* **61**, 1894.
1939. (With M. CALVIN.) The colour of organic substances. *Chem. Rev.* **25**, 273.
1940. (With G. T. SEABORG.) The acidity of aromatic nitro compounds toward amines. The effect of double chelation. *J. Amer. Chem. Soc.* **62**, 2122.
1940. (With T. T. MAGEL and D. LIPKIN.) The absorption and re-emission of light by *cis*- and *trans*-stilbenes and the efficiency of their photochemical isomerization. *J. Amer. Chem. Soc.* **62**, 2973.
1941. (With D. LIPKIN.) The dissociation of tetraphenylhydrazine and its derivatives. *J. Amer. Chem. Soc.* **63**, 3232.
1941. (With D. LIPKIN and T. T. MAGEL.) Reversible photochemical processes in rigid media. A study of the phosphorescent state. *J. Amer. Chem. Soc.* **63**, 3005.
1942. (With T. T. MAGEL and D. LIPKIN.) Isomers of crystal violet ion. Their absorption and re-emission of light. *J. Amer. Chem. Soc.* **64**, 1774.
1942. (With D. LIPKIN.) Reversible photochemical processes in rigid media: the dissociation of organic molecules into radicals and ions. *J. Amer. Chem. Soc.* **64**, 2801.
1942. (With J. BIGELEISEN.) The initial step in the action of acids on tetraarylhydrazines. *J. Amer. Chem. Soc.* **64**, 2808.
1943. (With J. BIGELEISEN.) The orientation of molecules produced photochemically in rigid solvents. *J. Amer. Chem. Soc.* **65**, 520.
1943. (With J. BIGELEISEN.) Methylene blue and other indicators in general acids. The acidity function. *J. Amer. Chem. Soc.* **65**, 1144.
1943. (With O. GOLDSCHMID, T. T. MAGEL and J. BIGELEISEN.) Dimeric and other forms of methylene blue: absorption and fluorescence of the pure monomer. *J. Amer. Chem. Soc.* **65**, 1150.
1943. (With J. BIGELEISEN.) The second order x bands in absorption spectra. *J. Amer. Chem. Soc.* **65**, 2107.
1943. (With J. BIGELEISEN.) The y bands in absorption spectra. *J. Amer. Chem. Soc.* **65**, 2102.
1943. (With J. BIGELEISEN.) Photochemical reactions of leuco dyes in rigid solvents. Quantum efficiency of photo-oxidation. *J. Amer. Chem. Soc.* **65**, 2419.
1943. (With J. BIGELEISEN.) Further photo-oxidation in rigid media. *J. Amer. Chem. Soc.* **65**, 2424.

1944. (With D. LIPKIN and T. T. MAGEL.) The light absorption and fluorescence of triarylmethyl free radicals. *J. Amer. Chem. Soc.* **66**, 1579.
1944. (With M. KASHA.) Phosphorescence and the triplet state. *J. Amer. Chem. Soc.* **66**, 2100.
1945. Rules for the absorption spectra of dyes. *J. Amer. Chem. Soc.* **67**, 770.
1945. (With M. KASHA.) Phosphorescence in fluid media and the reverse process of singlet-triplet absorption. *J. Amer. Chem. Soc.* **67**, 994.
1945. (With M. CALVIN.) Paramagnetism of the phosphorescent state. *J. Amer. Chem. Soc.* **67**, 1232.