

Essay

In between Worlds: G.N. Lewis, the Shared Pair Bond and Its Multifarious Contexts

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Abstract: In this paper, I will look at the rather convoluted discovery process which gave birth to the concept of the shared electron pair bond as developed by G.N. Lewis, to be subsequently appropriated by the American founders of quantum chemistry, and highlight the complex relations between conceptual development and the different contexts in which ideas are created and presented. I will show how the successive installments of Lewis's model of the chemical bond were supported by and gained credence from an epistemological background in which Lewis explored the relations of chemistry to physics. Furthermore, they were shaped by the changing public contexts in which the successive metamorphoses of the ideas took place and their epistemological background was outlined and explored. The complexities which are always associated with a discovery process can therefore be illuminated if one pays attention to different interactive realms—the conceptual, epistemological, and the presentational one.

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Introduction

In the preface to the jointly authored textbook on thermodynamics, G.N. Lewis (1875–1946) used an architectural metaphor to describe the construction of science. A collaborative enterprise, the scientific landscape reveals, nonetheless, “its cathedrals, built by the efforts of a few architects and of many workers.”¹ Lewis fell under his own definition of architectural scientists, builders of cathedrals. Coming of age at the turn of the century, when 19th century science and technology were undergoing deep changes, Lewis was an attentive witness and active participant in disciplinary readjustments and innovations. He played an outstanding role in the development of physical chemistry in the United States of America and in the United Kingdom and, furthermore, directly influenced the work of the American founders of quantum chemistry—Linus Pauling and Robert Sanderson Mulliken.²

John Slater wrote an unpublished autobiography titled *A Physicist of the Lucky Generation*. The manuscript is held at the Slater Papers, American Philosophical Society. His work on the chemical bond, which is being commemorated in this special issue, was but a piece of a lifelong effort to explore the frontiers of chemistry and physics. One might even claim that Lewis was

as much a physicist as he was a chemist. This hybrid outlook which was shared by many American scientists of the “lucky generation”³ he helped to mold, and which was partially a result of an institutional environment congenial to many American universities, is of key importance in understanding the context which favored the genesis and development of quantum chemistry in the United States. The versatility revealed by Lewis enabled him to cross disciplinary boundaries with extreme ease, to be sensitive to problems of articulation of neighboring disciplines or of specialties within disciplines, and to use his scientific contributions as a starting point for a philosophical reflection on the methods, structure and unity of science. This state of affairs might also explain why he became the author of the first paper on relativity to be published in 1908 in the United States, and one of its most outspoken advocates. As far as I know he is a singular case, in that it was a (physical) chemist, not a physicist, a mathematician or an astronomer, who responded to relativity ahead of members of supposedly more receptive scientific communities. In one paper, he derived the mass-energy relation from his former ideas on light pressure, without the help of the

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relativity principle, in another, he derived Einstein's equations from conservation laws together with the principle of relativity. His imprint was left forever in quantum theory by christening light corpuscles as photons.⁴ Or why he paid so much attention to facets of science other than strict scientific production. Eager to build around him a group whose organization mirrored his own views about chemistry and science, his impact extended to educational and popularization realms.

Lewis's ideas on the chemical bond have been discussed in the history of science literature since the 1970s. To R.E. Kohler, we owe a perceptive analysis of the development of Lewis's ideas in the context of other chemical atomic models and its appropriation by Irving Langmuir. John Servos subsequently discussed them in the context of the development of physical chemistry in the USA, and K. Gavroglu and A. Simões in the context of the emergence of quantum chemistry in the USA. Gavroglu and T. Arabatzis further discussed this topic in the framework of the two contrasting models of atomic structure—models which came to be known as the chemical and the physical atom.^{2(b),5}

Here I will go back to some of these issues by taking a different viewpoint. I will look at the rather convoluted discovery process which gave birth to the concept of the shared electron pair bond as developed by Lewis, to be subsequently appropriated by the American founders of quantum chemistry, and highlight the complex relations between conceptual development and the different contexts in which ideas are created and presented. I will show how the successive installments of Lewis's model of the chemical bond were supported by and gained credence from an epistemological background in which Lewis explored the relations of chemistry to physics. Furthermore, they were shaped by the changing public contexts in which the successive metamorphoses of the ideas took place and their epistemological background was outlined and explored.

In fact, three different contexts of presentation were covered, from teaching classes (1902) to academic publications, in either paper (1913, 1916) or book (textbook) form (1923), revealing Lewis's exploration of different modes of scientific communication, all deemed equally important. The use of multiple channels to explore and convey his broad approach to science was further extended in an incursion into the popularization realm. In the *Anatomy of Science* (1926) Lewis offered considerations on the contrasting methods of chemistry and physics, to which he returned in a scientific paper published in the first volume of the new *Journal of Chemical Physics* (1933).

As Lewis himself revealed, his preliminary static cubic atomic model emerged while attempting to teach students the known periodic and polarity properties of elements. For Lewis, the contexts of discovery and justification were irrevocably intertwined. Lectures, textbooks, and popular books could all be sites for molding and exploring novel ideas. Lewis's bond model evolved in a stable epistemological framework and in multifarious presentational contexts, which often played the double and simultaneous role of contexts of justification and of discovery. The complexities which are always associated with a discovery process can therefore be illuminated if one pays attention to different interactive realms—the conceptual, epistemological, and the presentational one.

Biographical Snapshot

Lewis was born in 1875 in West Newton, Massachusetts, and he was a precocious child able to read at the age of three.⁶ He was educated at home until 1889 when, having moved with his family to Nebraska, he attended the preparatory courses to enter university. He stayed at the University of Nebraska for two years but moved to Harvard in 1893, receiving a B.Sc. in 1896 and a Ph.D., in 1899, with a dissertation on electrochemical potentials supervised by the physical chemist Theodore William Richards, the first American Nobel laureate in chemistry. He stayed at Harvard until 1905. His Harvard years were interrupted by two outings and a one-year "exile." In 1900, he visited the Mecca and Medina of physical chemistry, staying six months with Walter Nernst in Göttingen and another six months with Wilhelm Ostwald in Leipzig. In 1904, he was granted a leave of absence to work as a chemist at the Bureau of Weights and Measures in Manila. In 1905, he joined Arthur Amos Noyes and his team of physical chemists at M.I.T., where he stayed for seven years. There, he laid the foundations for his important work on thermodynamics based on the systematic measurements of free energies. In 1912, he accepted the offer of President Benjamin Ide Wheeler and became dean and chairman of the College of Chemistry at the University of California at Berkeley. This move was part of Wheeler's renewed attempt to revitalize chemistry through the promotion of physical chemistry. On Wheeler's efforts to build a strong Department of Chemistry at Berkeley.^{5c}

Lewis moved west with a group of able young chemists and many innovative ideas in mind for the reform of teaching and research in chemistry. Everybody was supposed to be comfortable in every division of chemistry, discussions were encouraged, and cooperation among researchers was fostered. Within a broad view of physical chemistry which encompassed nuclear physics, radiochemistry, and biochemistry, Lewis supervised R.C. Tolman, who later became one of the top theoretical physicists at Caltech, and was also responsible for recruiting R. Oppenheimer and E. Lawrence to come to Berkeley.⁷ According to one of Lewis's former students:^{6b}

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 corridors, arguing vehemently about these "rain 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 and his group reformed the undergraduate curriculum by reducing the number of basic courses, striving to develop a critical spirit even at the freshman level, and producing several good teachers and textbook writers. For example, Lewis and Merle Randall's *Thermodynamics and the Free Energy of Chemical Substances* shaped the "newer generation" of chemists.¹ Addressed to a diversified audience including beginners, readers with interest in the philosophical implications of thermodynam-

ics, and all sorts of researchers, the book materialized Lewis's integrated view of the many faces of science, and his belief that physics and mathematics should be integral components of the newer generation of chemists. Breaking up with textbook tradition, it shared functions of a traditional textbook and an introduction to research.

Lewis's scientific interests covered subjects as disparate as thermodynamics, valence theory, and theory of radiation and relativity. In the decade after 1923, Lewis returned to quantum theory and relativity. His imprint was left forever in quantum theory by christening light corpuscles as photons.^{4c,4d} Lewis began thinking about all of them while at Harvard. In the last decade of his career, Lewis tried to devise a new chemistry of deuterium compounds, a field he abandoned for research on photochemistry in 1938. He also delved into the field of American prehistory, geology (he wrote a paper on the thermodynamics of glaciation), and economics (he wrote two papers on price stabilization). Lewis worked until the very end of his life. He died in the laboratory while performing an experiment on fluorescence.

Lewis's work on thermodynamics was crucial in convincing chemists of the utility of this discipline to the study of chemical systems, at a time when thermodynamic potentials were mainly known to physicists. The few chemists who had heard about them could hardly see how they could be applied to complex real chemical systems. Lewis realized that an exact chemical thermodynamics should be built upon the concepts of free energy and entropy, not upon heats of reaction as the calorimetric school advocated. At MIT, he made an extensive compilation of data on the free energy of formation of inorganic compounds, later enlarged by data on organic compounds, which was to be of particular utility in the chemical industry. He proceeded to show chemists how thermodynamics could be extended to deal with real systems. He introduced new concepts such as fugacity, a function with the dimensions of pressure which measured the tendency of a substance to change from one chemical phase to another, and activity, a function with the dimensions of concentration which measured the tendency of substances to induce change in chemical systems. Although these concepts never played a central unifying role in chemical thermodynamics as envisioned by Lewis, they proved fundamental to study deviations from the behavior of ideal systems. In this manner, Lewis became one of the very first, together with van't Hoff, to convince chemists of the importance of mathematical theories in chemistry, and that chemical thermodynamics provided such a theory.

Partaking of the tradition of physical chemistry of Ostwald, van't Hoff, and Svante Arrhenius, which aimed at transforming a largely empirical and qualitative chemistry into a new chemistry where mathematics and theory had a prominent role to play, Lewis did not abide to their choice to distance themselves from the emphasis on structure typical of organic chemistry. At Harvard, he introduced the static cubic atom as a model of atomic structure to explain the chemical bond (1902). These embryonic ideas were probably discussed extensively at MIT, and later matured into two papers, the first published in 1913, and the second in 1916. As an outcome of this work Lewis introduced a new theory of acids and bases, in which bases were defined as electron pair donors and acids as molecules

that could accept electron pairs. Finally, Lewis's ideas on valence were wrapped up in the book *Valence and the Structure of Atoms and Molecules* (1923).⁸

An Atomic Model Conceived for Teaching Purposes

According to Lewis's recollections, offered in *Valence* 20 years after the event, the cubic atom emerged while attempting to explain to an elementary class in chemistry some of the known properties of valence—polarity and periodicity⁹—in terms of the new ideas about electrons. In what relates to periodicity, one should recall that by the end of the 19th century a whole family of elements was added to the periodic table, following the discovery of the inert gases, so that it was accepted that physical and chemical properties of elements were periodic functions of their atomic weights in such a way that elements arranged by increasing atomic weights fall into different periods and eight different groups. With J.J. Thomson's final proof of the existence of electrons (1897), and the identification of electrons in radioactivity, all necessary preliminary steps for an electronic theory of valence were taken. This was the context of Lewis's 1902 proposal, which remained unpublished, and was described much later, in the 1923 textbook:⁸

1. The electrons in an atom are arranged in concentric cubes.
2. A neutral atom of each element contains one more electron than a neutral atom of the element next preceding.
3. The cube of eight electrons is reached in the atoms of the rare gases, and this cube becomes in some sense the kernel about which the larger cube of electrons of the next period is built.
4. The electrons of an outer incomplete cube may be given to another atom, as in Mg^{++} , or enough electrons may be taken from other atoms to complete the cube, as in Cl^- , thus accounting for "positive and negative valence."

Unclear at this time on many questions, such as the disposition of positive charges in the atomic arrangement, but certain of many crudities of his model, no further publicity was given to it beyond discussions with colleagues and students.

Chemical and physical considerations were at the origin of the cubic atom. Chemical, and specifically, valence considerations, enforced a valence shell completed with eight electrons, while the cubical configuration was the result of assuming that electrons obeyed Coulomb's repulsion law and therefore tended to be as far apart as possible. The model expressed in electronic terms the "empirical" rule of eight according to which rare gases show no chemical reactivity. For Lewis, in rare gases, including helium, chemical inertness meant that their outer cube was completely filled with electrons, while chemical reactivity signified that reacting atoms had incompletely filled outer cubes. The cubic structure was the most symmetrical arrangement of eight electrons which ensured that they were the farthest apart. Sensing the limited applicability of laws, such as Coulomb's, at the atomic level, he guessed that "it seems inherently probable that in elements of large atomic shells (large

atomic volume) the electrons are sufficiently far from one another, so that Coulomb's law of inverse squares is approximately valid, and in such cases it would seem probable that the mutual repulsion of the eight electrons would force them into the cubical structure."¹⁰

Lewis's 1902 theory offered a "remarkably simple and satisfactory" explanation of the formation of polar compounds such as sodium chloride (NaCl). It fitted nicely the old electrochemical theory by specifying what was meant by the transfer of electricity from one part of the molecule to another in a chemical union. For Lewis, chemical reactions in polar compounds proceeded by the transfer of electrons from an atom to the other, as electropositive elements such as Na could give off their outer electrons to an electronegative atom as Cl, and conversely electronegative elements could readily capture electrons from an electropositive one.

Shortly after Lewis's first thoughts on the cubic atom, which remained unpublished, the explicit statement of the transfer of an electron from an atom to another as the paradigm for chemical bonds appeared in print in one form or another. In the framework of Richard Abegg's theory of electrovalence (1904), each element had two kinds of valences—normal valence and contravalence (Translated in the framework of Lewis's theory, normal valence meant the number of electrons that occupied the outer cube, whereas contravalence meant the number of places left vacant in the outer cube.)—whose arithmetical sum was eight: "The sum 8 of our normal and contra valences has therefore the simple significance as the number which represents for atoms the points of attack of electrons; and the group number or positive valence indicates how many of the eight points of attack must hold electrons in order to make the element electrically neutral."⁸ Relative to this scheme, Lewis's unknown cubic atom had the advantage of explaining the stability of the eight electrons as a straightforward consequence of the choice of a cubic structure to represent atoms.

In 1907, the nature of the chemical bond was addressed by the physicist J.J. Thomson in the framework of his "plum-pudding" theory of atomic structure, first proposed in his Silliman Lecture delivered at Yale University. It became the dominant atomic model until Ernst Rutherford's suggestion of the planetary atom. The chemical bond resulted also from a transfer of electrons from an atom to another, interpreted as the production of a "unit tube of electric force between the two atoms."¹¹ Furthermore, it provided a physical interpretation to the lines by which chemists represent bonds in graphical formulae: they represented "the tubes of force which stretch between the atoms connected by the bond,"¹¹ and should be replaced by vectors symbolizing these tubes. For example, if an electropositive element is united to an electronegative element, the line bond uniting their symbols should be replaced by a vector pointing in the direction of the electronegative element (vector bond).

Chemists in the USA realized quickly that Thomson's prestige could be used as an invaluable asset for the polar theory, and that his ideas were worth exploiting further. This program was vigorously implemented in the United States by a group of able chemists to which belonged K. George Falk, John M. Nelson, Harry S. Fry, Julius Stieglitz, and William A. Noyes.⁹ⁱ

The Shared Electron Pair: Inventing Quantum Mechanisms with Classical Entities

But dissenting voices tarnished the period of hegemony of polar theory. In 1913, the year of the publication of Bohr's model of the dynamic planetary atom, a few criticisms resulted in the adoption, by Lewis and others, of a dualistic view, according to which the usual polar bonds should be complemented by nonpolar bonds. This is especially clear in Lewis's paper "Valence and Tautomerism," in which he reviewed the chemical properties of both polar and nonpolar compounds, and represented their opposite characteristics in a table, side by side. At this time, opposing properties forced Lewis to "recognize the existence of two types of chemical combination which differ, not merely in degree, but in kind."¹² Still unsure about how to accommodate nonpolar bonds in the framework of the cubic atom, Lewis could only suggest vaguely that "we need only assume that upon each atom there are definite regions, or points, at which direct connection to similar points on other atoms may be made, and that the number of occupied regions on a given atom is the valence number of that atom."¹²

In polar substances, a certain number of electrons is transferred from one atom to another, yet Lewis felt uncomfortable about the idea of vector bonds as it assumed the possibility of labeling electrons: "The arrow purports to show between which atoms an electron has passed, but since all electrons are alike, and presumably leave no trail behind them, we cannot say that atom *A* loses an electron to atom *B* and atom *C* to atom *D*, but only that atoms *A* and *C* have each lost an electron and atoms *B* and *D* have each gained one."¹²

In the following years, different dualistic theories came to the chemical fore.^{5a,5b} After having been an important advocate of the polar theory of valence, J.J. Thomson (1914) changed his mind and defended the existence of two sorts of chemical bonds.¹³ Polar bonds were formed by the transfer of electrons, and were represented by a single vector bond as in his polar theory, whereas nonpolar bonds were associated with two physical bonds, two tubes of force connecting two electrons, one from each of the interacting atoms. Thus, for Thomson the number of bonds in structural formulae should be doubled whenever bonds were nonpolar. For example, a single bond in a structural formula of a nonpolar compound was represented by two vectors with opposite directions symbolizing that two electrons, one coming from each atom, were involved in each bond; in the case of double bonds in nonpolar compounds, four electrons were involved and the bond was represented by two pairs of opposite vectors.

For William C. Arsem (1914) it was obvious that molecules such as H₂ should have bonds that did not involve an actual electron transfer.¹⁴ He imagined that one single electron was responsible for both sort of bonds, but in nonpolar bonds the electron, instead of being transferred from one atom to another, remained in oscillation between the two atoms, becoming simultaneously part of both atoms. Surprisingly, Arsem assumed that the molecule of H₂ possessed just one electron. Because of the oscillatory movement, the same electron was shared by both atoms.

Alfred L. Parson's atomic theory (1915) introduced both a two electron bond and a cubic octet, and conceived the physical origin of the chemical bond as magnetic.¹⁵ The electrons should

be represented by circular currents (magnetons), arranged at the corners of cubic octets. The magnetic moment generated by them was the source of chemical bonding and the stability of the octet. For Parson, there were three different kinds of chemical union associated with three different kinds of bonds (bonds such as in H—H, H—Cl, and Cl—Cl). In the case of bonds such as in Cl—Cl, and in order for both atoms to have complete octets, Parson proposed that magnetons from both atoms formed a “mobile group” which oscillated between the atoms, forming a full octet in one atom, and then in the other.

All three models introduced the idea of electrons shared by two atoms, a fact acknowledged by Lewis in the case of Thomson and Parson’s models.^{8,10} Evidence that Arsem’s model might have influenced Lewis is provided in Kohler.^{5a} It is quite probable that the shared pair bond was the outcome of appropriating the former ideas, exploring and translating them into the framework of Lewis’s own picture of the cubic atom. For example, if one took the step of representing two atomic cubes with an edge shared, Thomson’s positive and negative bonds would coalesce in one single type of nonpolar bond, and the need for vectors and tubes of force would disappear. It is possible that van’t Hoff stereochemistry might have influenced Lewis’s search for a three dimensional atomic model. Both van’t Hoff and Lewis wished their models to be “visualizable.” This was the revolutionary idea of the 1916 paper, in which Lewis further explored the cubic atom, presenting his results in axiomatic form and using a formal deductive style of presentation:¹⁰

1. In every atom is an essential *kernel* which remains unaltered in all ordinary chemical changes and which possesses an excess of positive charges corresponding in number to the ordinal number of the group in the periodic table to which the element belongs.
2. The atom is composed of the kernel and an *outer atom or shell*, which in the case of the neutral atom, contains negative electrons equal in number to the excess of positive charges of the kernel, but the number of electrons in the shell may vary during chemical change between 0 and 8.
3. The atom tends to hold an even number of electrons in the shell and especially to hold eight electrons which are normally arranged symmetrically at the eight corners of a cube.
4. Two atomic shells are mutually interpenetrable.
5. Electrons may ordinarily pass with readiness from one position in the outer shell to another. Nevertheless, they are held in position by more or less rigid constraints, and these positions and the magnitude of the constraints are determined by the nature of the atoms and of such other atoms as are combined with it.
6. Electric forces between particles which are very close together do not obey the simple law of inverse squares which holds at greater distances.

While in the first and second postulates Lewis merely restated the basic assumptions of his unpublished 1902 theory, in the third postulate Lewis added to the former “rule of eight” a new “rule of two.” This rule embodied two new sorts of experimental data, one provided by chemical, the other by physical methods, both pointing to the fact that almost all compounds contain an even

number of electrons. The exceptions, molecules such as NO, NO₂ or ClO₂, were called “odd molecules,” and in a way their existence confirmed the “rule of two,” for they all were unstable molecules that tended to react to form compounds by pairing. On the other hand, new spectroscopic data resulting from Moseley’s X-ray spectrum analysis showed helium to include just two electrons, contrary to Lewis’s former assumption.

The “rule of two” was the property that in electronic terms corresponded to the novel concept of shared electron pairs introduced in the fourth postulate. Interpreted jointly with the third postulate, the fourth postulate meant that a chemical bond may occur due to the interpenetration of cubic atomic shells, and this may happen precisely by the sharing of a pair of electrons. The second and fourth postulates taken together meant that in interpenetrable atomic shells an electron does not belong exclusively to one single atom. The electron is shared by two distinct cubic atomic shells, and hence neither atom loses or gains an electron. Reassessing the interconnections between both types of bonds, Lewis now claimed that while only in purely polar molecules the electron transfer is complete, in the framework of the new theory “it is not necessary to consider the two extreme types of chemical combination, corresponding to the very polar and very nonpolar compounds as different in kind, but only as different in degree.”¹⁰

Further clarification of the specific way in which the interpenetration of atomic shells occurred was provided by the visual representation of the chemical union of two cubic atoms. Single bonds such as in F₂ were represented by the sharing of an edge. Double bonds such as in O₂ were represented by the sharing of a face. The cubic atom could also account for intermediate states of valence, in which an electron pair was unequally shared between atoms.

The two last postulates addressed some physical implications of an atomic model conceived mainly to answer chemical questions and supported both by chemical and physical data. In the fifth postulate, Lewis seemed to be struggling once more with the idea of “indistinguishability.” This postulate arose as a possible way of interpreting the nondetection of the so-called “intra-atomic” isomers, which differ in the positions occupied by the electrons of the outer cube. As Lewis put it: “If the electrons of the atomic shell could at one time occupy one set of positions and at another time another set, and if there were no opportunity for ready transition from one of these sets of positions to another, we should have a large number of isomers differing from one another only in the situation of the electrons in the atomic shell In most cases it is evident that they do not exist, and we must assume, therefore, considerable freedom of change from one distribution of electrons in the shell to another.”¹⁰

Finally, in the last postulate Lewis imposed a restriction on the applicability of Coulomb’s law, limited to distances greater than the atomic separation, in order to justify his idea of shared electron pairs as the mechanism for bond formation. In this move Lewis was possibly helped by the awareness that Bohr’s atomic model also violated the classical laws of electromagnetism. If the atomic world behaved differently from the macroscopic realm, to limit the validity of Coulomb’s law was not as big a heresy. In any case, Lewis tried to explain the attraction between two electrons in physical terms. The justification stemmed from their magnetic

properties. Properly oriented magnetic electrons accounted for the stability of paired electrons.

In the new model, and contrary to Lewis's former assumptions, both types of valence had a common cause. They were different in degree but not in kind, so that molecules could pass "from the extreme polar to the extreme nonpolar form, not *per saltum* but by imperceptible gradations."¹⁰ This statement verbalizes a breakthrough in Lewis's understanding of the nature of the chemical bond. As of 1902, the cubic atom merely represented polar bonds. In 1913, Lewis advocated a dualistic theory which admitted two types of bonds, different not only in degree, but also in kind. But he still had no way to represent nonpolar bonds. In 1916, the novelty was the accommodation of the two types of bonds into a single framework, with the straightforward representation of nonpolar bonds by the sharing of an edge or a face. Although it was not clear as of 1902 (or 1913) how to accommodate nonpolar bonds in the framework of the cubic atom, in 1916 Lewis was probably helped by his awareness that models, such as those of Thomson, Arsem or Parson, had already embodied the idea of electrons held in common by two atoms.

Lewis's choice of representing the atom as a succession of concentric cubes played a crucial role in the suggestion of the shared electron pair bond.¹⁶ This novel idea, which grew out of the exploration of a pictorial representation in the context of suggestions by other scientists and Lewis own musings over the matter, introduced a new theoretical entity—the shared electron pair—into chemistry, and entailed a reappraisal of the notion of individuality. Furthermore, it enabled Lewis to extend the scope of his 1902 theory in order to accommodate in one single framework the mechanism of bonding in polar and nonpolar substances, and by that token to unify inorganic chemistry and structural organic chemistry. At the same time, the new theoretical entity fostered a move from a three-dimensional representation to a more abstract pictorial representation in which shared electron pairs and free pairs were depicted by means of double dots. Diatomic molecules such as Cl₂, O₂, and N₂ were represented, respectively, by a single, a double, and a triple bond. The advantages of the double dot notation, which went much beyond a mere descriptive role, were immediately seized by Lewis. As he stated: "While the two dots of our formulae correspond to the line which has been used to represent the single bond, we are led through their use to certain formulae of great significance which I presume would not occur to anyone using the ordinary symbols."¹⁰

In the long run, chemical imagery retained the dot notation but forgot the cubic atom, a process for which Lewis himself contributed. One could hardly see how to account for the tetrahedral stereochemistry of the carbon atom, or the free rotation around a single bond, or even for triple bonds, in the framework of the cubic atom. To accommodate these chemical facts, Lewis modified his model by moving the electrons from the corners of the cube to its edges, so that the four pairs defined the four corners of a tetrahedron. Two tetrahedra, attached by one or two corners represented, respectively, single and double bonds. Two tetrahedra joined at three corners or one face represented triple bonds. But this was, after all, the same as abandoning the cubic representation altogether. One can understand why Lewis dis-

carded his cubic atom so easily. Lewis's methodology had been from start "to find, apart from any *a priori* consideration, just what atomic structure best explains known chemical facts."¹⁰ If the picture was found wanting Lewis would not hesitate to modify it, and in the process of transition to the tetrahedral atom, he was guided by the increasing awareness of the dominance of the "rule of two" relative to the empirical "rule of eight." As Lewis acknowledged "in the case of elements with lower atomic weights than lithium, . . . the *pair* of electrons forms the stable group, and we may question whether in general the pair rather than the group of eight should not be regarded as the fundamental unit."¹⁰

In 1919, the cubic atom and the shared pair bond were taken up by Irving Langmuir.¹⁷ Langmuir elaborated Lewis's theory and did such a good job in popularizing it that the Lewis–Langmuir theory (as it came to be known) was widely discussed and accepted.

Could Chemists Afford to Ignore Bohr's Atom?

Whereas Lewis's model had been introduced to explain chemical phenomena such as valence, Bohr's model was better suited to explain physical phenomena such as spectroscopic data.¹⁸ Right after finishing "The Atom and the Molecule" Lewis initiated a correspondence with Bohr to get him to stay one semester in Berkeley and to give the Hitchcock Lectures on theories of atomic and molecular structure. In the end Bohr was unable to come. (Archives for the history of quantum physics, Bohr Scientific Correspondence, BSC4, Letters Lewis to Bohr, February 8, 1916, June 30, 1916, Letters Wheeler to Bohr, February 11, 1916, Letter Bohr to Wheeler, March 24, 1916, Letters Bohr to Lewis, March 2, 1916, May 22, 1916, August 10, 1916, August 26, 1916).

During the period from 1916 to 1923, Lewis kept thinking about how to harmonize his model with Bohr's model of atomic structure.^{5d–f} The existence of two different atomic models—the chemists' and the physicists'—was a problem for a chemist so physically minded as Lewis, a problem ever more pressing in view of the increasing sophistication of Bohr's model, but which Lewis believed could be solved trivially. By the time of the publication of *Valence* Lewis had already convinced himself, and tried to convince his readers, that the contradictions between the two models could be easily removed, championing the view that the chemical and the physical atom could be merged into one unified description of atomic structure.

The appearance of Lewis's *Valence* in 1923 epitomizes very important aspects of Lewis's contributions. Published in a series of scientific and technological monographs by the American Chemical Society, the book is a hybrid between a scientific monograph and a textbook, offering a state of the art review of valence and atomic theories in a limpid style but never refraining to survey recent trends in the topic, however controversial they might appear. It voices openly and unrepentantly Lewis's views as well as his agenda for the smooth articulation of chemistry and physics, of which the merging of the two pictures of the atom was an exemplary instance, and his belief that besides being involved in the construction of science, a true scientist should be involved in teaching and in writing in order to reach

out as wide an audience as possible. Faithful to his active promotion of discussion and cooperation among scientists, the book voices his daily practice, and is dedicated to his colleagues and students because “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.”⁸

Believing that a scientist well informed in physics and chemistry had a crucial role to play in the study of molecular structure, Lewis’s study of Bohr’s atomic model assured him that “while the orbit of one electron may as a whole affect the orbit of another electron, we should look for no effects which depend upon the momentary position of any electron in its orbit.”⁸ In that case, it was possible to translate the positions of the electrons in the static model into the average positions of more or less mobile electrons in the atomic model of the old quantum theory, and this equivalence would be fundamental in bringing together the chemical and physical evidence into a unified theory of atomic structure.

By 1923, Lewis adduced to the chemical evidence, he had previously gathered in favor of electron pairing, new physical evidence pertaining to ionization potentials and spectroscopy.^{8,19} Going one step further he suggested a physical explanation for the mechanism of pairing. His magnetochemical theory of chemical affinity was based on the assumption that in an atom or molecule electronic orbits act as magnets in such a way that two orbits conjugate with one another so as to eliminate magnetic moment; and that the condition of maximum chemical stability for atoms, except for hydrogen and helium, corresponded to a valence shell completed with four pairs of electrons situated at the corners of a tetrahedron.

An obvious consequence of these rules was the prediction that odd molecules would reveal magnetic moment, so that chemical unsaturation went hand in hand with magnetic unsaturation, in the sense that every condition increasing unsaturation, or residual affinity, made the substance more paramagnetic. On the contrary, diamagnetism would go hand in hand with chemical saturation. Owing to the incipient stage of development of a physical theory of magnetism, the physical basis of the magnetochemical theory remained no more than a mere conjecture which Lewis predicted could be clarified by “experiments of the type of Stern and Gerlach.”⁸ Two years later, in 1925, the mysterious phenomenon of electron pairing was connected with Pauli’s exclusion principle and electron spin. A particular spin configuration (purely quantum phenomenon) accounted for the existence of attractive (exchange) energy, and gave way to a classical picture of the *sharing* of two electrons.

When *Valence* was still in proof, Lewis was invited to give the introductory address at the general meeting of the Faraday Society held in Cambridge, England, in 13–14 July of 1923 with the purpose of discussing “The Electronic Theory of Valence.” Captivated by Lewis’s theory, British physical and organic chemists made it the basis of the new field of physical organic chemistry, dominated, during the 1930s, by the study of reaction mechanisms. The organization of the meeting was a convincing proof of their interest in and willingness to use Lewis’s theory of valence. A diametrically opposite reaction characterized the

response of the chemical community in postwar Germany which, following the general political mood, proudly cultivated a style of scientific isolationism from all Anglo-American influence.²⁰

The symposium was attended by physicists J.J. Thomson, William H. Bragg, and R.H. Fowler, and by several of the most outstanding physical and organic chemists in Britain and America. Besides Lewis, Robert Robertson, Thomas M. Lowry, Arthur Lapworth, William A. Noyes, and Nevil Vincent Sidgwick were present.²¹ The opening address by Lewis was a brilliant summary of the book on *Valence* just sent for publication.²² Lewis’s main points were the reconciliation of the physical and the chemical atom, the formation of the electron pair, which he dubbed “the cardinal phenomenon of all chemistry,” as well as the explanation of the main aspects of his valence theory and the associated magnetochemical theory.

Fowler and Sidgwick, who were to play a crucial role in laying the ground for the development of quantum chemistry in British soil,²³ spoke along the same lines as Lewis. Both tried to show how Bohr’s theory of atomic structure could be used to clarify the physical nature of valence. Fowler started by pointing out that there was not as yet a safe guide to molecular structure which would play the role as Bohr’s theory of the hydrogen atom played in relation to atomic structure.²⁴ Then, he suggested that the next step in the development of a theory of the electronic structure of molecules would possibly be based on chemical evidence as to the nature of valences. Finally, he proceeded to summarize some of the conclusions regarding molecular structure reached by the application of Bohr’s atomic model to chemical ideas on covalence. Sidgwick added to Bohr’s theory of the atom the hypothesis that “the orbit of each “shared” electron includes both of the attached nuclei,”²⁵ and then explained how this conception of the nonpolar link as shared electrons occupying binuclear orbits enabled one to derive known chemical facts.

The application of the electronic theory of valence to organic chemistry was amply discussed in the meeting. In the section on organic chemistry, the opening remarks by Robertson and the introductory address by Lowry shared the emphasis on a new era initiated by the application of physical ideas to valence. They both voiced the obligation to conform to the proved demands of the physicist as the most fruitful path for chemistry to follow:²⁶

Since molecules as well as atoms must have an electronic structure, it is clear that chemists or physicists, or more probably a team containing representatives of both groups, must take up the task of determining the electronic structure of molecules. This investigation may mean either much or little for the development of chemistry. It may be that the electronic formulae will be merely a translation of the traditional structural formulae of inorganic and organic chemistry, adding nothing but a new nomenclature to science. All the precedents are, however, strongly against this since, whenever a clearer conception of molecular structure has arisen, chemists have always found a new way of regarding old facts, and even a new nomenclature for them has provided a powerful stimulus to investigation and has led to a great outbreak of new researches.²⁷

The first presentation of the views of this new school of physical organic chemistry was provided by Sidgwick's textbook on *The Electronic Theory of Valence*. Tellingly, the book starts with a remark very much along the lines of Robertson's and Lowry's respective addresses, so that one may claim that even before the advent of the new quantum mechanics, the Anglo-American approach to the study of valence and molecular structure, materialized by Lewis's contributions and the questions debated at the 1923 Faraday Meeting, was characterized by an acute awareness that the fruitful course open to the chemist was indeed the explanation of the chemical facts of valence and molecular structure in terms of the concepts of atomic and molecular physics, so that the mastery of the laws of physics was an essential precondition for being successful in that endeavor. At the time most chemists felt threatened by such an approximation to physics. According to Sidgwick, some would prefer to "use symbols with no definite physical connotation to express the reactivity of the atoms in a molecule, and may leave to the subsequent progress of science to discover what realities these symbols represent."²⁸

Lewis's Leitmotiv and *The Anatomy of Science*

In 1926, when the transition from the old quantum theory to the new quantum mechanics was complete and the discussions on foundational issues were emerging, one year after the introduction of spin and the statement of Pauli principle, and in the very same year when Heisenberg introduced the notion of exchange forces acting between electrons to account for the stability of helium, Lewis revisited his views on the relations of chemistry to physics in the context of a broader reflection on the structure and methods of science. They were elaborated in a book on popularization called interestingly *The Anatomy of Science*, in which Lewis dissected with wit and lightness the inner mechanisms of science in a literary way reminiscent of the contrasting play of light and shadows revealed in Rembrandt's painting "The lesson of anatomy of Dr. Tulp."

The book was the 20th volume in a series resulting from the endowed Silliman Lectures delivered at the University of Yale, which included books by J.J. Thomson, Walter Nernst, Ernst Rutherford, and Arrhenius. The lectures aimed at proving the omnipotence of God as manifested in the natural and moral world and explicitly avoided controversial issues in theology to privilege approaches stemming "from the domains of natural science and history, giving special prominence to astronomy, chemistry, geology, and anatomy."²⁹ They are illustrative of the appeal of natural theology in 20th century America.

Lewis offered to his popular audience "a glimpse of the inside of the scientist's workshop, his habits, his tools, and his raw materials,"²⁹ and considered to have been able to articulate "a singularly satisfying little philosophy,"²⁹ although one equally distant from the raw materialism of many men of science and the disguised theology of classical metaphysics.

It is a conceptual analysis of the structure of science ordered in a very Comtean way, going from mathematics, to physics, chemistry, and biology, centered on the analysis of foundational concepts and the role of mathematics in science. Concepts sur-

veyed go from the concept of number to the physical concepts of space, time, matter, motion, light, and the quantum, entropy, and probability, to finally address chemistry, and specifically the organization of organic chemistry in a chapter called revealingly "The non-mathematical sciences." The book ends with an incursion into the biological sciences. Under the heading "Life; body and mind," several questions are discussed such as the distinction between the animate and the inanimate world, and the compatibility between determinism and free-will.

The organization of the book does not purport to convey any hierarchical assessment of the organization of the sciences, in which the mathematically grounded ones would dominate over the nonmathematical ones,²⁹ but just that the first group involves fewer concepts, addresses less complicated problems, and therefore is more amenable to a greater degree of abstraction and idealization, to such an extent that its grounding in practice is less clearly recognized. These considerations are all the more interesting as Lewis introduces the reader to a discussion of the conceptual foundations of relativity and quantum physics, revealing once again his endorsement of recent advances in physics and his belief that they had become fundamental building-blocks in the new architecture of science. At the same time, he makes clear from start how many erroneous views have been put forward concerning the methods of science. His passionate opinion is conveyed in the following poetically plain way.²⁹

I take it that the scientific method, of which so much has been heard, is hardly more than the native method of solving problems, a little clarified from prejudice and a little cultivated by training. A detective with his murder mystery, a chemist seeking the structure of a new compound, use little of the formal and logical modes of reasoning. Through a series of intuitions, surmises, fancies, they stumble upon the right explanation, and have a knack of seizing it when it once comes within reach. I have no patience with attempts to identify science with measurement, which is but one of its tools, or with any definition of the scientist which could exclude a Darwin, a Pasteur, or a Kekulé.

The scientist is a practical man and his are practical aims.

He does not seek the *ultimate* but the *proximate*. He does not speak of the last analysis but rather of the next approximation. His are not those beautiful structures so delicately designed that a single flaw may cause the collapse of the whole. The scientist builds slowly and with a gross but solid kind of masonry. If dissatisfied with any of his work, even if it be near the very foundations, he can replace that part without damage to the remainder. On the whole, he is satisfied with his work, for while science may never be wholly right it certainly is never wholly wrong; and it seems to be improving from decade to decade.

The theory that there is an ultimate truth, although very generally held by mankind, does not seem useful to science except in the sense of a horizon toward which we may proceed, rather than a point which may be reached.

Certainly this description of the workings of the scientist *qua* practical man fitted like hand a glove to Lewis's own scientific

practice. The road to the suggestion of the shared electron pair and its subsequent metamorphoses was guided by such strong beliefs about the workings of science.

In the chapter on chemistry, and later on, in a paper which assessed Lewis's contributions in the context of the problematic of quantum chemistry (1933), Lewis contrasted the different features of theories in chemistry and physics. He presented structural organic chemistry as the paradigm of a chemical theory, later to be defined as an analytical theory in the sense it is grounded on a large body of experimental material from which the chemist attempts to deduce a body of simple laws which are consistent with the known phenomena.^{8,29,30} The paradigm of a physical theory would be called, by contrast, a synthetic theory to stress that the mathematical physicist starts by postulating laws governing the mutual behavior of particles and then "attempts to synthesize an atom or a molecule."³⁰ When the attempt is successful he has a weapon of extraordinary power which enables answers to questions quantitatively which at best could be answered qualitatively by the other method. Of course, an inaccuracy in a single fundamental postulate may completely invalidate the synthesis, while the results of the analytical method can never be far wrong, resting as they do upon such numerous experimental results.

An alternative classification was introduced which opposed the convergent method of the chemist to the divergent method of the physicist.²⁹ Whereas the analytic (or convergent) method gave qualitative answers to the problems posed by the chemist, the synthetic (or divergent) method provided quantitative solutions. And although the analytical method did not depend on the correctness of the postulates guessed by the physicist as the synthetic method, it could never be far wrong, resting as it did on numerous experimental facts.

The recognition of these differences led him to suggest in the first place, and to defend throughout the successive refinements of his theory, the electron pair and the chemical bond of shared pairs as the two essential features of molecular structure, "the minimum demands of the chemist which must eventually be met by the more far-reaching and quantitative work of the mathematical physicist."³⁰ This statement was voiced in the first volume of the *Journal of Chemical Physics*, which resulted from the acknowledgment that the new subdiscipline of quantum chemistry was well under way. It was especially created to house papers "too mathematical for the *Journal of Physical Chemistry*, too physical for the *Journal of the American Chemical Society* or too chemical for the *Physical Review*."

For Lewis it was the interplay between the qualitative interventions of chemistry and the quantitative interventions of physics that expressed the constitutive methodology of quantum chemistry. One should note that quality and quantity are not used in their usual sense when they are associated with chemistry and physics, respectively. Chemistry's phenomenological laws acquire their qualitative reliability because of the quantitative exactness of chemistry, whereas the quantitative results of mathematical physics have their particular significance on account of the qualitative character of the initial hypotheses of physics. Articulating the methodological novelties of quantum chemistry, in such a manner, brings forth a series of complicated and subtle factors contributing to its becoming, which cannot be reduced to proposed solutions for the technical difficulties met

with the application of quantum mechanical methods to the problems of chemistry. Many of the founders and early contributors to quantum chemistry were influenced by Lewis, learning fast and well their lesson.

Early Responses, Future Impact

In 1928, the young Pauling wrote a short note to the Proceedings of the National Academy of Sciences pointing out that London's valence theory provided essentially the theoretical underpinning of Lewis's phenomenological theory.³¹ To Lewis he confided: "It pleases me very much that in the new atomic model the salient features of the Lewis atom have been reproduced as much as those of the Bohr atom" (Pauling Papers, Box 58, G.N. Lewis 1913–1947, Reprints and Correspondence, Letter Pauling to Lewis, 7 March 1928. Ava Helen and Linus Pauling Papers, Oregon State University Library, Special Collections). But despite such a recognition, Lewis noted that in one respect his original valence theory was never adopted neither in London's paper nor in Pauling's contributions, where too much emphasis was placed upon the origin of the paired electrons: "It was an essential part of my original theory that the two electrons in a bond completely lose their identity and cannot be traced back to the particular atom or atoms from which they have come; furthermore that this pair of electrons is the only thing which we are justified in calling a bond" (Pauling Papers, Box 58, G.N. Lewis 1913–1947, Reprints and Correspondence, Letter Lewis to Pauling, 1 May 1928. Ava Helen and Linus Pauling Papers, Oregon State University Library, Special Collections). Later, Lewis reiterated this objection, and went further in denying that any clarification, beyond calculational possibilities, was brought about by Heitler and London's contributions: "The work of Heitler and London made it possible to calculate the energy of some simple systems containing two electrons shared by two atoms. While their calculations were of utmost importance as a step towards the quantitative study of such systems, I cannot admit that it threw any further light upon the phenomenon of pairing."⁵⁹

Starting in 1929, and lasting for five years, Pauling delivered lectures at the University of Berkeley upon Lewis's invitation. During the second semester of 1929 he taught two courses, one about "Quantum mechanics with chemical applications," the other "The size of ions and other ionic properties" (Pauling Papers, Box 58, G.N. Lewis 1913–1947, Reprints and Correspondence, Letter Pauling to Lewis, 2 January 1929. Ava Helen and Linus Pauling Papers, Oregon State University Library, Special Collections). They were such a success that Lewis confided to Mayer: "they seemed to me the best lectures we have ever had and I scarcely missed a lecture" (The Bancroft Library, University of California, Berkeley, Lewis Correspondence, CU-30, Box 3, Folder on Mayer 1929–1941, Letter Lewis to Mayer, 3 May 1929). In 1931, Pauling delivered a series on "The nature of the chemical bond," which Birge announced to Mulliken claiming enthusiastically: "certainly we are on the threshold of a very large new development" (The Bancroft Library, University of California, Berkeley, Birge Correspondence, Box 33, Folder Jan–Mar 1931, Letter Birge to Mulliken, 18 April 1931). Considering himself as to some extent a "student of Lewis" (Pauling Papers, Box 212, LP Berkeley Lectures: Quantum Mechanics

1929–1933, introduction to first lecture on “The nature of the chemical bond.” Ava Helen and Linus Pauling Papers, Oregon State University Library, Special Collections). In the opening paragraph to the first paper of the series on “The nature of the chemical bond,” Pauling presented his program as an extension of Lewis’s approach to chemistry and defined the major methodological guidelines to be followed in order to proceed to clarify the nature of the chemical bond (Later on, the book, Pauling, L. *The Nature of the Chemical Bond and the Structure of Atoms and Crystals: An Introduction to Modern Structural Chemistry*; Cornell University Press: New York, 1939, was dedicated to Lewis who was overjoyed by it: “I have returned from a short vacation for which the only books I took were a half dozen detective stories and your “Chemical Bond.” I found yours the most exciting of the lot. I cannot tell you how much I appreciate having a book dedicated to me which is such a very important contribution. I think your treatment comes nearer to my own views than that of any other authors I know and there are very few places where I could possibly disagree with you; and those perhaps because I have not thought about the thing sufficiently.” In Pauling Papers, Box 58, G.N. Lewis 1913–1947, Reprints and Correspondence, Letter Lewis to Pauling, 25 August 1939. Ava Helen and Linus Pauling Papers, Oregon State University Library, Special Collections).³²

In that same year, Mulliken proposed to tackle the same questions from another perspective for which concepts such as the shared pair bond “should not be held too sacred.”³³ In 1932, he reiterated his first impressions: “there are no compelling reasons, either empirical or theoretical, for placing primary emphasis on electron pairs in constructing theories of valence.”³⁴ On the contrary, he gave prominence to Lewis’s “rule of eight,” and further considered his approach to be closer to Lewis in that electrons were not deemed localized in between the atoms.

Despite their differences about the constitutive elements of their theories but not about methodological matters,³⁵ Pauling’s and Mulliken’s contributions to quantum chemistry were informed by and indebted to Lewis’s, not only in strict scientific terms but also by inheriting a philosophically minded scientific outlook, already evident in the period up to 1933, when all three were contributors to the same volume of the new journal. This was also the year in which Sidgwick published his book *Some Physical Properties of the Covalent Link in Chemistry*,³⁶ stemming from his lectures at Cornell, in which he focused on the various physical methods available to measure bond properties. Not incidentally, the introductory lecture discussed “The relations of physics to chemistry,” and voiced opinions reminiscent of Lewis’s own ideas. For all those eager to conquer the territory opened up by quantum chemistry, it became crucial to understand the changing relationships among neighboring disciplines such as chemistry, physics, and even mathematics, in order to secure for quantum chemistry an autonomous status through the articulation of its own distinctive methodological guidelines and ontological commitments.

Conclusion

Lewis exemplifies his own definition of the scientist *qua* architect–builder of cathedrals. As well as cathedrals are human arti-

facts conceived to mediate between the terrestrial and the celestial world, Lewis lived, literally and figuratively, in between-worlds. He took part in the transition from the nineteenth to the twentieth century and from classical to quantum science. He positioned himself at the interface between the worlds of chemistry, physics, and mathematics, and as a scientist he did not separate his scientific practice from complementary activities as a lecturer, textbook writer, and a science popularizer.

However, while cathedrals are architectural closed works, in the sense that they do not withstand further adjustments and readjustments without an adulteration of their purported aims, Lewis’s model of the chemical bond is a good illustration of Umberto Eco’s open works. (*La definición del Arte*, Martinez Roca, S.A.: 1970). In this chapter, which stemmed from a talk delivered at a conference in 1958, Eco tries to analyze the ways in which contemporary works of art differ from traditional ones. Traditional works of art are characterized by completeness and definiteness, and they are expected to give way to different responses on the part of viewers which can be accommodated in the expectations of their creators. On the contrary, contemporary works of art often reveal an openness contrary to the aforementioned characteristics. They may not be complete in the strict sense, may undergo changes and adaptations, revealing kaleidoscopic properties, and the interpretations put up by their viewers may reveal unexpected and changing viewpoints. Eco explores this idea not only in what relates to painting but also architecture, literature, music, venturing to refer even to logic and science.³⁷ As well as there are examples of architectural open works, whose structural features may be modified and adjusted to the functions users envision for the building at a certain point of its history, the utmost plasticity and potential for appropriation of Lewis’s model made it survive the transition from classical science to quantum mechanics. The model’s openness offered its creator and newcomers the possibility of reinvention of some of its constitutive features together with new perspectives for future developments. Born when the role of electrons was still a mystery, when the idea of quantum particles and of properties such as spin or indistinguishability were still ahead, the model was developed in different contexts and articulated empirical evidence of different provenances, undergoing in the process modifications, from a three- to a two-dimensional model, amenable in any case to pictorial representations dear to chemists, to be finally incorporated in different ways in the framework of the work of the first generation of the American founders of quantum chemistry. The initial shortcomings of Lewis’s novel idea of the pairing of electrons, pointed by Lewis himself, became in the end the basis for the success of its future appropriation, on account of its potential to foster and incorporate novel adjustments and readjustments, to outrun and outlast its own multiform contexts of production.

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