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A PLACE IN HISTORY: WAS LINUS PAULING A REVOLUTIONARY CHEMIST?

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In 1998 the American Chemical Society published the 75th anniversary issue *of Chemical and Engineering News* (1). In preparation for the anniversary issue, the journal provided the opportunity for approximately 175,000 ACS members to nominate their choices for the "Top 75 Distinguished Contributors to the Chemical Enterprise" since 1923, using a ballot published in the magazine. Readers could nominate up to twenty people, living or dead, American or non-American.

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The result was a list of more than 1,200 individuals, giving a top-75 group in which four chemists far outpolled the next 71. The top four were Linus Pauling, Robert B. Woodward, Glenn Seaborg, and Wallace Carothers (2). The contributions for which Linus Pauling was cited in the poll were the nature of the chemical bond; valence bond theory; concepts of electronegativity, resonance and hybridization; and the application of structural chemistry to biological molecules (3).

A different kind of poll was taken by the British journals *New Scientist* and *New Society* some twenty years earlier, using a questionnaire published in May 1975. That poll sought to assess readers' images and stereotypes of scientists by asking open-ended questions such as, "When I think of a scientist, I think of . . . "The poll received approximately 1600 responses, of which 119 came from professional chemists. Of the scientists, past and present, who were most frequently mentioned in readers' responses, Pauling's name was the fifteenth most cited. Others included Darwin and Einstein, Galileo, Newton and Pasteur, and, among contemporary scientists, Jacob Bronowski, Fred Hoyle, and Peter Medawar (4).

In the *New* Scientist poll, professional and popular-science readers seem to have mentioned Pauling, like Bronowski and Medawar, on the basis of public image and public fame in the 1970s, whereas the *Chem. Eng. News* poll more clearly reflects judgments by Pauling's professional peers in the field of chemistry. Both polls point to a generalization that we hardly need to prove: that Linus Pauling is perceived both among chemists and among members of the general public as one of the most important figures in twentieth-century science.

Yet, we may ask, was Linus Pauling what may be called a revolutionary figure in the history of chemistry, and in the history of science more generally? Is his role in twentieth century science comparable to Galileo in the seventeenth century or Lavoisier in the eighteenth century or Pasteur in the nineteenth century? What makes a revolutionary reputation in science and who defines it: scientists, historians, or the wider public? The actors or the observers?

By way of addressing these questions, I will begin by describing some recent interpretations of the eighteenth-century Chemical Revolution and its embodiment in the historical figure of Antoine Lavoisier. I then will turn to a discussion of the aims and achievements of Linus Pauling, beginning with his earliest plans and ambitions in the 1920s. I shall conclude by re-opening the question of Pauling's place in history, as defined by scientists, historians, and the public.

Revolutions, Revolutionaries, and Lavoisier

In Bernard Cohen's book *Revolution in Science*, Professor Cohen traces the changing meaning of the word "revolution," from the sense of "turn" or "return," as in "turn of the wheel" or "turn of Fortune," to the implication of a historical break and transformation. In the political realm, eighteenth century writers used the new meaning of "revolution" in reinterpreting England's rebellion or civil war of 1688 as a "Glorious Revolution," and eighteenth-century Frenchmen soon applied the word "revolution" to political events of the 1790s in France (5).

In the realm of the sciences, Bernard Le Bovier de Fontenelle wrote in the early 1700s of the recent revolution in mathematics and mechanics associated with the name of Isaac Newton (6). More to our immediate concern, Antoine Baumé wrote in 1773 of a revolution in chemistry which had begun with the discovery of fixed air (7). That same year of Baumé's printed remark, Antoine Lavoisier wrote privately in a laboratory notebook that his work on the fixation and release of airs seemed "destined to bring about a revolution in physics and in chemistry (8)." At that moment, as Larry Holmes has stressed, Lavoisier likely thought of himself as participating in a revolutionary movement begun by others, not of himself as initiating a revolution. We have evidence of Lavoisier's view in a letter of 1774 that he sent to the Royal Society of Edinburgh, along with a gift of his *Opuscules physiques et chymiques*. In the letter, Lavoisier lauded the "illustrious savant" Joseph Black for Black's theory of fixed air "that seems to prepare a revolution in physics and chemistry (9)."

The next generations of chemists after Lavoisier certainly thought of him as a founding father of a new chemistry, but the idea received a new twist from the French Alsatian chemist Adolphe Wurtz in 1869, on the eve of the Franco-Prussian War. In what became an understandably controversial statement, Wurtz wrote that "Chemistry is a French science. It was founded by Lavoisier, of immortal memory .... he was at once the author of a new theory and the creator of the true method in chemistry (10)."

As France's Third Republic was established in the mid-1870s, Lavoisier was reclaimed by French scientists and politicians as a symbol explicitly of the modern, moderate, and scientistic French Republic. Lavoisier had been a member of the liberal wing of civil servants and political activists in the *ancien régime*. Lavoisier had been a reformist member of Louis XVI's tax-collecting agency, the Ferme Générale. He had been an innovative administrator in charge of the nation's gunpowder Arsenal. He had been an alternate deputy to the States General when it convened in 1789 (11). Yet, as a former member of the Ferme Générale and a prominent member of the academic elite, Lavoisier had been personally disliked and under suspicion by some members of the Revolutionary Committee. Arrested in 1793, he was executed in 1794. Letters removed from his home included an unsigned letter to Mme. Lavoisier with the prescient and damning words, if evidence were needed of disloyalty: "This most beautiful revolution will make our streams run with blood and plunge us into total anarchy (12)."

By fortuitous coincidence, the 1889 centenary commemoration of the French Revolution was also the centenary of the publication of Lavoisier's textbook, the *Elements of Chemistry*. Edouard Grimaux, a chemist at the Ecole Polytechnique, published a biography of Lavoisier (13), as did Marcellin Berthelot, chemist at the Collège de France and member of the French Senate. It was Berthelot who applied the phrase "chemical revolution" to Lavoisier's achievements alone, attributing to one heroic figure what often had been described as a collective transformation of ideas (14).

By the end of the nineteenth century, then, Lavoisier's image had become firmly an image of scientific hero and political martyr. The latter image only enhanced the former one. The iconography of Lavoisier's memory clearly demonstrates this double image (15).

It includes sketches of Lavoisier in the laboratory and a magnificent portrait by Jacques-Louis David of Lavoisier and Mme. Lavoisier. There is also a contemporaneous sketch made of Lavoisier while in prison and a newer dramatic painting of 1876 by L. Langenmantel commemorating "The Arrest of Lavoisier (16)."

Further, the integration of the scientific and the political revolutions is absolutely faithful to the historical record, as registered in the well-known letter from Lavoisier to Benjamin Franklin in February of 1790. A "revolution . . . has taken place in . . . human knowledge since your departure from Europe," Lavoisier wrote to Franklin, describing opposing camps of phlogistonists and anti-phlogistonists, but "having brought you up to date on what is going on in chemistry, it would be well to speak to you about our political revolution (17)."

"The Arrest of Lavoisier" by L. Langernmantel (1876). Courtesy and permission of Special Collections, University Libraries, University of Pennsylvania

Linus Pauling and the Remaking of Modern Chemistry

I will return to Lavoisier and the eighteenth-century chemical revolution, but let me turn now to Linus Pauling, the son of a pharmacist, born in Portland, Oregon in 1901. In January 1917 he entered Oregon Agricultural College, where he quickly attracted the attention of his college instructors, who enlisted him to teach freshman- and sophomore-level chemistry courses while he was still a student (18).

While preparing his chemistry lectures in 1920, Pauling ran across Irving Langmuir's papers of 1919 on the structure of atoms and the new electron theory of valence (19). Langmuir's publications led Pauling back to the 1916 paper of G. N. Lewis, whose work and person he admired for the rest of his life (20). From then on, Pauling rarely had the chemical bond far from his mind. Nor did he relinquish the fascination with molecular form and structure that first engaged him in a course on the crystallography of metals with Samuel Graf. This focus on structure and on the chemical bond became permanent leitmotifs for Pauling's chemical career.

During the summer of 1922 before entering graduate school at the California Institute of Technology, Pauling worked for the Oregon Highway Department near Astoria. By this time, he had proposed marriage to Ava Helen Miller, a student in his chemistry class of the previous spring. Pauling's summer letters to Ava Helen give insights into the aims and ambitions of the young chemical engineering graduate. Not surprisingly, he was "anxious to get to California in order to find how long it will take me to get my Ph.D. and to see how well I'll get along with really good men in the realm of science." Indeed, he wondered whether he might be a "second A.A. Noyes (21)." (Noyes was director of Caltech's chemistry division.) At summer's end, Pauling wrote Ava Helen of his desire to live up to his ambitions and her expectations. He wrote that he aspired to the Nobel Prize, "something which connotes a lifetime of unselfish effort, as does the Perkin's [*sic*] Medal (22)." In later years, a very elderly Pauling penned a note drawing attention to his youthful reference to the Nobel Prize. The Perkin Medal, in fact, eluded him (23).

After he arrived at Caltech in the fall of 1922, Pauling's coursework included thermodynamic chemistry with Noyes; statistical mechanics and atomic structure with Richard Chace Tolman; kinetic theory with Robert Millikan; advanced dynamics with Arnold

Sommerfeld's student Paul Epstein; and statistical mechanics and quantum theory with the visiting Austrian theoretical physicist Paul Ehrenfest (24).

Pauling wrote Ava Helen of his ambition to "lead my classes, except radiation" where he intended merely "to get along." He was ecstatic following his first meeting with the Physics and Astronomy Club in October 1922. He wrote his fiancée that the clubroom had held a collection of physicists who are "the best in the country." Even though he was a new graduate student, fresh from Corvallis, Pauling bragged to Ava Helen that he "argued a moment with Tolman and thus felt puffed up (25)." Ambitious and conscious of his ambition, Pauling moved ahead in his studies.

Pauling's first paper with Roscoe Dickinson appeared in 1923, on the structure of the mineral molybdenite (MoS_2). In the next three years, Pauling authored or co-authored a dozen crystal-structure publications (26). His 1926 application for a Guggenheim Foundation Fellowship focused on something different, however. Pauling aimed to take up Professor Sommerfeld's challenge for (27):

> working out a complete topology of the interior of the atom and, beyond this, a system of mathematical chemistry, that is, one which will tell us the exact position of the electrons in the atomic envelope and how this qualifies the atom to form molecules and to enter into chemical compounds.

He wanted to take part in a new reductionist and mathematical program for chemistry.

Returning in late 1927 from eighteen months in Munich, Copenhagen, and Zurich, Pauling became an assistant professor in theoretical chemistry. He published an explanation in *Chemical Reviews* of Walter Heitler and Fritz London's application of quantum mechanics to the hydrogen molecule, as well as treatments of the hydrogen molecular ion by Oyvind Burrau and Friedrich Hund (28). By 1928 Pauling had begun to sketch out his own novel ideas for theoretical treatment of the chemical bonds for methane. The notion was to do away with the distinction between **2s** and **2p** energy sublevels for the four shared electron-pair bonds in methane, in order to get the identical tetrahedral valences of the carbon atom (29).

Pauling lectured at Berkeley and Caltech during 1929 to 1934, developing for students and faculty the notion of "changed quantization" of electron energy levels in the carbon atom and setting up wave functions to represent classical valence, or electron-pair bonds, in compounds like carbon dioxide, benzene, and methane. He also began writing a series of papers on "The Chemical Bond," published during 1931 to 1933, some of the papers being co-authored with Albert Sherman and George Wheland (30).

Pauling and his collaborators at Caltech were by no means the only ones working along these lines. Harvard University's John Slater, whom Pauling first met in Cambridge in 1929, was using the same Heitler-London approach, while Robert Mulliken was taking up the strategy of Friedrich Hund and Erich Hückel for assuming that electrons of the outer shells of atoms can move in molecular orbitals spanning an array of atoms as a whole, rather than behaving as single electrons orbiting one atomic nucleus alone (31). They all were devising methods for creation of a new mathematical chemistry. But Pauling's first paper in the "Chemical Bond" series was pathbreaking. William Lipscomb later said, simply, that this paper "changed chemistry (32)."

In July 1935 Pauling and E. Bright Wilson, Jr. completed the highly technical *Introduction to Quantum Mechanics with Applications to Chemistry*. The claims they make at the beginning of the rigorously mathematical book are modest, but profound (33):

> The subject of quantum mechanics constitutes the most recent step in the very old search for the general laws governing the motion of matter. . . . it is now realized that the combining power of atoms and, in fact, all the chemical properties of atoms and molecules are explicable in terms of the laws governing the motions of the electrons and nuclei composing them.

While the *Introduction to Quantum Mechanics* is highly mathematical, Pauling's *Nature of the Chemical Bond and the Structure of Molecules and Crystals* is not. This book is based on lectures he gave at Cornell University, and it first appeared in 1939. Here Pauling laid out in a largely nonmathematical way the theory of the electron valence-bond, including the concept of resonance in conjugated molecules, linking the theory of the chemical bond to explanations of molecular structure.

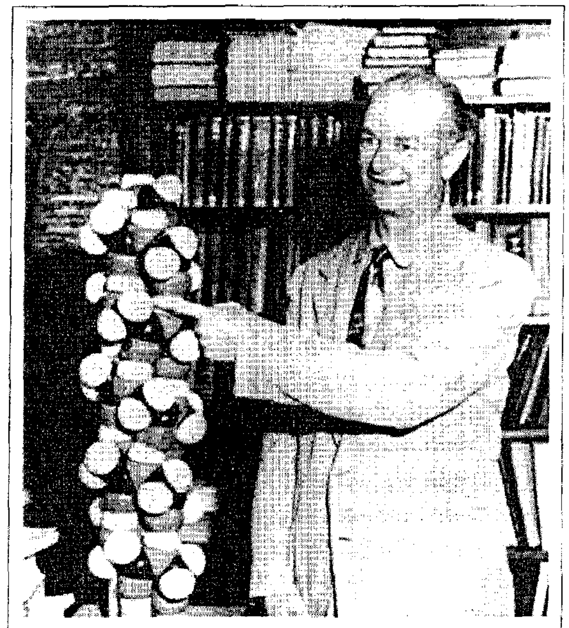
Like Lavoisier's textbook on *Elements of Chemistry*, Pauling's textbook on *The Chemical Bond* changed the way scientists thought about chemistry, presenting chemistry as a disciplinary field unified by an underlying theory. By demonstrating how the characteristics of the chemical bond determined the structure of molecules and how the structure of molecules determined their properties, Pauling showed for the first time, as Max Perutz said, "that chemistry could be understood rather than being memorized (34)." In a fiftieth anniversary tribute to Pauling's *Chemical Bond* in 1989, Eugene Garfield noted that this fifty-year old scientific book ranked in the top ten scientific publications cited in the ISI database since 1945, and that it ranked among the top five most cited books. Remarkably, in the year 1988 alone, *The Chemical Bond* received over 600 citations, while only around 30 publications received 60 or more citations (35). This is an extraordinary record for any scientific book.

Pauling pioneered the use of drawings and diagrams in chemical textbooks. His innovations can be seen in the first versions of a general chemistry textbook which Pauling began making available in 1941 to freshmen at Caltech as a lithographed volume. Pauling's *General Chemistry*, finally published by William Freeman in 1947, included a profusion of illustrations ranging from X-ray and electron-diffraction photographs, to graphical constructions of atoms and molecules, to cartoon-like pictures of electron densities drawn as fuzzy orbital clouds around central atoms. The pictures were designed by the professional artist and licensed architect Roger Hayward, who began making illustrations for Pauling's lectures as early as 1933 (36).

There is yet another way in which Pauling helped transform chemistry in the late 1930s and 1940s. In the fall of 1938 Pauling initiated correspondence with Joseph Hirschfelder about the usefulness of three-dimensional molecular models for teaching and research: the so-called "space-filling" models (37). As Eric Francoeur has noted, the German chemist H. A. Stuart had begun designing this new kind of molecular model in 1934 (38). Hirschfelder and Pauling corresponded about the diameters to be used for representation of the atoms, partly on the basis of Pauling's work with Lawrence Brockway on covalent radii and bond-angle values from electron diffraction studies of carbon compounds (39). By 1939 the Fischer Scientific Company was selling kits of the models, with advertisements suggesting their use not only for studying spatial relationships and steric hindrance, but also for testing hypotheses about molecular structure (40).

By this time Pauling's research was moving away from further technical development of quantum chemistry and toward the study of the structure and function of large, biologically significant molecules, by use of both physical methods of instrumentation and chemical methods of modeling (41). By the late 1940s Pauling's chemistry laboratory was making space-filling models, as well as other molecular models, for the use of Pauling and his collaborators in studying the structures of polypeptides, proteins, and other molecules, including, by the early 1950s, DNA. The models were designed by Pauling, Robert Corey, Verner Schomaker, and J. H. Sturdivant (42).

As has often been recounted in histories of the DNA "double helix," news circulated at Caltech in 1951 that Pauling's team was constructing protein models precise to the finest details. There are several accounts of Pauling's dramatic announcement of the protein structure to a packed lecture room at Caltech in 1951. These accounts, like other on-the-spot descriptions of Pauling's lectures, helped create at the time a powerful image of Pauling as master strategist of molecular structure, a presumption that James Watson, for example, acknowledged in describing his and Francis Crick's success in 1953 in solving the DNA structure by using Pauling's methods (43):



Linus Pauling with alpha-helix model of protein, circa 1957. From the Ava Helen and Linus Pauling Papers, Special Collections, Oregon State University.

> We could . . . see no reason why we should not solve DNA in the same way.

At Caltech in the spring of 1951, Pauling entered the biology lecture room flanked by assistants carrying, among other things, something tall wrapped in cloth and bound with string, like a piece of statuary. Everyone knew that this was "the Model." In Tom Hager's account (44):

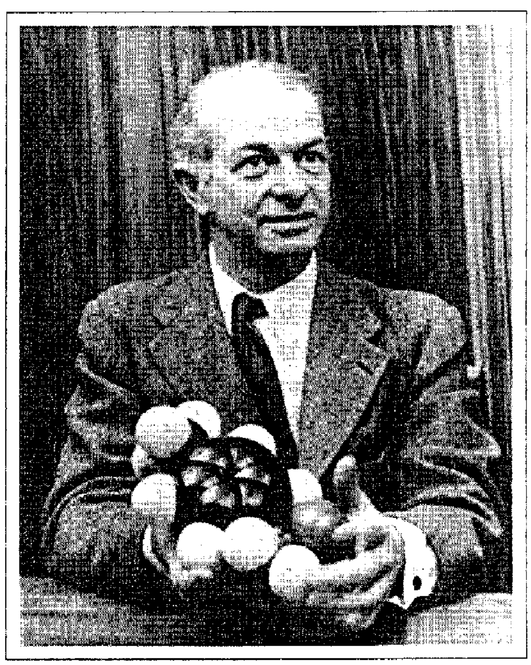
> He held up a child's set of soft plastic pop-beads and snapped them together to show how amino acids connected. After a suitable introduction, he started moving toward the Model . . . . [and] unveiled it with a grand flourish: a beautiful, multicolored model of his tight spiral, the alpha helix. It was the first time many in the audience had seen a space-filling molecule. . . . It looked 'real,' . . . . it had depth and weight and density, a kind of visual impact that no other model had ever approached.

A September 1951 issue of *Life* magazine carried a large photograph of a grinning Pauling pointing to his space-filling model of the alpha helix, with the headline "Chemists Solve a Great Mystery"—presumably the mystery of life (45).

Linus Pauling and Matters of Politics

Although *Life* magazine had an idolizing attitude toward Pauling in 1951, this view would change in the course of the next decade. In 1951, *Life* praised the accomplishments of Pauling, who would receive the Nobel Prize in Chemistry in 1954. *Life's* editors also expressed sympathy in 1951 with the chemist Pauling whose theory of chemical resonance was currently a subject of vilification from Soviet "officials" for its alleged bourgeois idealism (46). However, by 1962 it was *Life* editors themselves who were vilifying Linus Pauling. What happened? Pauling had become a political figure. Following World War II, Pauling, like many scientific colleagues, joined organizations concerned with atomic-science and atomic-bomb issues. He gave invited talks mostly to local California groups, including a left-wing organization of artists and intellectuals in Hollywood that became a target of the House un-American Activities Committee's investigation of communism in the motion picture industry (47).

In late 1947 an anonymous member of the American Chemical Society contacted the Federal Bureau of Investigation (FBI) with concerns about the political views of the Society's new president-elect. In 1948, while Pauling was on a visiting appointment in Oxford, FBI agents quizzed his co-workers, neighbors, and Caltech administrators, looking through his Caltech personnel file to detect any signs that Pauling was a communist sympathizer (48). The theoretical chemist whose resonance theory of chemical bonding was under attack by Soviet ideologists now found himself suspected of communist sympathies. Cleared of any wrongdoing by a Caltech committee in December 1950, Pauling was denied a US passport in 1952, preventing his attending a Royal Society discussion on proteins. His passport was restored, then denied again (49). When reports came out in the spring of 1954 of radiation poisoning of Japanese fishermen following the US explosion of a hydrogen bomb at Bikini Atoll, Pauling connected the problem of radiation poisoning and genetic damage from fallout to his own recent research interests in DNA and nucleic acids as carriers of inherited characteristics, including mutations in genes (50). Discussions with biologist Barry Commoner and physicist Edward Condon resulted in the idea of a written worldwide appeal for a ban on the testing of nuclear weapons. In early 1958, Linus and Ava Helen Pauling presented a petition with 9,000 signatures to Dag Hammarskjold at the United Nations. In response, *Life* magazine carried a negative story about Pauling, highlighting criticism from physicist Edward Teller and Rand analyst Albert Latter that "The worldwide fallout is as dangerous to human health as being one ounce overweight (51)." Teller and Pauling debated each other in live coverage on KQED television in San Francisco, with no clear resolution of technical issues for viewers (52). By 1960 the Senate Internal Security Committee, which had branded Pauling a fellow traveler in 1956, subpoenaed him to explain possible communist involvement in the nuclear-test ban movement (53).



Linus Pauling with a model of the sulfanilamide molecule, circa 1954. From the Ava Helen and Linus Pauling Papers, Special Collections, Oregon State University.

In the fall of 1963, when it was announced that Linus Pauling would receive the 1962 Nobel Peace Prize, *Life* magazine, carrying the extraordinary headline "A Weird Insult from Norway," stated that the limited test-ban treaty had nothing whatsoever to do with Pauling or the 1958 petition to the UN (54). Caltech's president, Lee Dubridge, praised Pauling's efforts for peace but publicly noted that many people in Pasadena and the scientific community had disapproved of his methods. Pauling resigned from Caltech (55).

In the last decades of his life, Pauling's concerns with genetics, molecular structure, and medical chemistry once again propelled him into the public limelight as he began to use his fame in a public campaign to establish Vitamin C as a cure for the common cold and, in huge doses, for cancer. Controversy over the merits of vitamins and other anti-oxidants in the treatment of cancer embroiled Pauling with members of the Mayo Clinic and the broader medical community (56). Pauling began to sound like a latter-day Anton Mesmer, fighting an entrenched medical and academic elite for the benefit of the public citizenry (57). His opponents, he charged, feared "monetary losses that would be inflicted on pharmaceutical manufacturers, professional journals, and doctors themselves" if the value of Vitamin C therapy were admitted (58). Pauling now spoke of a revolutionary age, saying that scientists should be radicals and not conservatives in their service to humanity (59).

Scientific Revolutions and Scientific Revolutionaries

As is well-known, Thomas Kuhn's analysis of *The Structure of Scientific Revolutions* insists upon puzzle-solving as an ordinary activity among scientists. Anomaly and crisis, followed by invention of a new paradigm or a new textbook tradition, are essential features of scientific revolution. Not everyone has agreed with Kuhn. In fact, most everyone has disagreed with some aspect or another of Kuhn's analysis, often by way of emphasizing histories of science as histories that are gradual transformations of ideas and disciplines rather than catastrophic ruptures with the past (60). Still there are markers of scientific change that seem to be a matter of common agreement among scientists and historians. New languages are invented, new textbooks are written, and new theories are superimposed on old theories, either ruling them out entirely, or limiting their applicability. New ways of seeing the world emerge. By and large, the terminology of "revolution", like the terminology of "tradition," is common and ubiquitous among scientists and historians.

What conclusions can be drawn in considering the legacies of Pauling and Lavoisier? In the case of Linus Pauling, as we have seen, Pauling did not set out to initiate a revolution in science, but he was eager to participate in the newest front of scientific advance. There was no crisis in chemistry in Pauling's youth, but there were puzzles and anomalies to be solved, for example, in understanding the bond structure of methane and benzene, and the length and energy of aromatic and conjugated bonds. The application of quantum mechanics to chemical electron bonds was an exciting new frontier, and Pauling and others succeeded in constructing a mathematical quantum chemistry rather quickly from the late 1920s to the mid-1930s. Pauling, more than some of his colleagues, was concerned to integrate these results with both the theoretical assumptions of classical organic structure theory and the empirical applications of new physical instruments, like X-ray diffraction. Like Lavoisier, Pauling's work ranged broadly across physics and chemistry, chemical and physical methods, mathematical and visual explanations, and biological and physical chemistry (61).

Like Lavoisier, too, Pauling saw clearly that the new chemistry he was helping to construct required a new language, new representations, and new textbooks. New principles had to be laid out at the beginning of chemical education, namely the principle of the electron-valence bond, including concepts of electronegativity, resonance and hybridization, and the principle of spatial architecture, with bonds, atoms, and molecules laid out precisely in three-dimensional space.

The *General Chemistry*, like *The Chemical Bond*, defined a new chemistry, just as assuredly as did the molecular models and model-building techniques associated with Pauling's name. By the 1960s, the high school chemistry curriculum in the United States was based on the chemical bond approach (CBA) of the 1959 high-school textbook *Chemical Systems* (62). The CPK, or Corey-Pauling Space Filling Models with Improved Koltun Connectors, became as common in chemical classrooms and laboratories as the periodic table (63). As Hoffmann and Woodward wrote in *Science* in 1970, a "revolution" had occurred "in our image of what molecules really look like and what we can conceive of them doing or not doing in the course of a chemical reaction (64)."

An irony at the end of Pauling's career, as at the end of Lavoisier's career, was the way in which political events turned him into a public figure about whom very strong emotions and judgments were elicited from both scientific colleagues and members of the body politic. In each case, the man's heroic status as scientist made him all the more controversial and, in the end, all the more visible as public figure and political victim. The political turns in Pauling's life, like Lavoisier's, were partly of his own making. The accusations of patriotic disloyalty were patently false, but allegations about intellectual arrogance and imprudent judgment were sometimes fair enough. With Pauling, as with Lavoisier, his long-term reputation as a revolutionary figure rests partly in the political dimensions of his life, which set him apart from many other scientists. Yet these political dimensions attract attention largely because his reputation as a great scientist had already been well established. Pauling's place in history is firm. Whether he will be regarded as a revolutionary figure of twentieth-century chemistry at the end of the twenty-first century is a matter that future generations of scientists and historians will decide.

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REFERENCES AND NOTES

1. *Chemical and Engineering News* first appeared as the News Edition of *Industrial and Engineering Chemistry* on January 10, 1923. See M. Jacobs and R. M. Baum, "Editors' Page," *Chem. Eng. News*, January 12, 1998, *76*, 7.
2. "Contributors to the Chemical Enterprise: C&EN's Top 75," *Chem. Eng. News*, January 12, 1998, 76, 171-185, on 171.
3. Ref. 2, p 181.
4. P. Hills and M. Shallis, "Scientists and Their Images," *New Scientist*, August 21, 1975, 471-475 (473). In order, from #1 to #15: Archimedes, the fictional "Prof. Branestawm," Bronowski, Marie Curie, Darwin, Einstein, Faraday, Enrico Fermi, Fleming, Galileo, Sir Fred Hoyle, Sir Peter Medawar, Newton, Pasteur, Linus Pauling.
5. I. B. Cohen, *Revolution in Science*, Harvard University Press, Cambridge, MA, 1985, 52-69.
6. Ref. 5, pp 90, 161.
7. Ref. 5, pp 233-234. In his introduction to a 1988 collection of essays, Arthur Donovan writes that the Chemical Revolution, "long recognized as one of the major turning points in the development of modern science, is arguably also the best example we have of a classic revolution in science." A. Donovan, "Introduction," in "The Chemical Revolution: Essays in_Reinterpretation," *Osiris*, 2nd series, **1988**, *4*, 5-12.
8. Quoted in D. McKie, *Antoine Lavoisier: Scientist, Economist, Social Reformer*, Henry Schuman, New York, 1952, 110; also Ref. 5, p 230.
9. See F. L. Holmes, *Antoine Lavoisier—The Next Crucial Year or The Sources of His Quantitative Method in Chemistry*, Princeton University Press, Princeton, NJ, 1998.
10. A. Wurtz, *A History of Chemical Theory*, trans. by H. Watts, Macmillan Publishing, London, 1869, 1. Alan Rocke argues that Wurtz's remarks were directed more at his own French rivals than at German ones. A. J. Rocke, *The Quiet Revolution: Hermann Kolbe and the Science of Organic Chemistry*, University of California Press, Berkeley, CA, 1993, 346.
11. A. Donovan, *Antoine Lavoisier: Science, Administration, and Revolution*, Blackwell, Oxford, 1993; as well as J. P. Poirier, *Antoine-Laurent Lavoisier*, Pygmalion, Paris, 1993; and Ref. 8.
12. The events and the letters are discussed in Ref. 8, pp 376-415.
13. E. Grimaux, *Lavoisier 1743-1794 d'après sa correspondance, ses manuscrits, ses papiers de famille et d'autres documents inédits*, Alcan, Paris, 1888. Grimaux used materials from Lavoisier's collected *Oeuvres*, which were being published by the French government: A. Lavoisier, *Oeuvres de Lavoisier publiées par les soins de son Excellence le Ministre de l'Instruction Publique et des Cultes*, J.-B. Dumas and E. Grimaux, Ed., Paris, 1862-1893, 6 vol.
14. M. Berthelot, *La Révolution chimique—Lavoiser*, Alcan, Paris, 1890. On this, see F. L. Holmes, *Eighteenth-Century Chemistry as an Investigative Enterprise*, Office for the History of Science and Technology, Berkeley, CA, 1989, 112-113; also, B. Bensaude-Vincent, *Lavoisier: Mémoires d'une révolution*, Flammarion, Paris, 1993, 374-378; and B. Bensaude-Vincent and I. Stengers, *A History of Chemistry*, trans. by D. Van Dam, Harvard University Press, Cambridge, MA, 1996, 86, 90.
15. On memory and commemorations, see B. Bensaude-Vincent, "Between History and Memory: Centennial and Bicentennial Images of Lavoisier," *Isis*, **1996**, *87*, 481-499.
16. See University of Pennsylvania Library, Center for Electronic Text and Image at http://www.library.upenn.edu/etext/smith/l/lavoisier.html.
17. Ref. 5, p 230.
18. Of twelve students who graduated in 1922 with Pauling in chemical engineering at OAC, six, like him, went on to receive Ph.D.'s. See T. Hager, *Force of Nature: The Life of Linus Pauling*, Simon & Schuster, New York, 1995, 50-51.
19. I. Langmuir, "The Arrangement of Electrons in Atoms and Molecules," *J. Am. Chem. Soc.*, **1919**, *41*, 868-934;

"Isomorphism, Isosterism and Covalence," *J. Am. Chem. Soc.*, **1919**, *41*, 1543-1559; "The Structure of Atoms and the Octet Theory of Valence," *Proc. Natl. Acad. Sci. U.S.A.*, **1919**, *5*, 252-259.

20. G. N. Lewis, "The Atom and the Molecule," *J. Am. Chem. Soc.*, **1916**, *38*, 762-785. I. Langmuir, "The Structure of Molecules," *BAAS Reports. Edinburgh. 1921*, **1922**, 468-469. Discussed in interview by John Heilbron with Linus Pauling, March 27, 1964, Pasadena, 1st of 2 sessions, p 8, Sources for History of Quantum Physics (Berkeley depository).
21. Letter from Linus Pauling (in Warrenton, Oregon) to Ava Helen Miller (in Corvallis), June 20, 1922, Courtesy of the Ava Helen and Linus Pauling Papers, Oregon State University Libraries (hereafter, Pauling Papers, OSU): LP Safe/1/1922x.06.20 LP.
22. Linus Pauling (Warrenton, Oregon) to Ava Helen Miller (Corvallis, Oregon), postmarked August 11, 1922, Pauling Papers, OSU: LP Safe/1/1922x.08.09 LP.
23. The Perkin Medal likely came to Pauling's attention as a newly established award of the American Section of the Society of Chemical Industry / Société de Chimie Industrielle, founded in 1918 in New York.
24. Linus Pauling's Guggenheim Foundation Fellowship application for 1926, Pauling Papers, OSU: LP Science/14.0101/folder 9. See J. R. Goodstein, *Millikan's School. A History of the California Institute of Technology*, W. W. Norton, New York, 1991, 96-98.
25. Letters from Linus Pauling (Pasadena) to Ava Helen Miller (Corvallis), October 2 and 4 or 5, 1922, Pauling Papers, OSU: LP Safe/1/1922x.10.02 LP and LP Safe / 1/1922x.10.04 LP.
26. See S. F. Mason, "The Science and Humanism of Linus Pauling (1901-1994), *Chem. Soc. Rev.*, **1997**, *26*, 29-39, (29-30).
27. Ref. 24: L. Pauling, Guggenheim Fellowship application for 1926, Pauling Papers, OSU.
28. L. Pauling, "The Application of the Quantum Mechanics to the Structure of the Hydrogen Molecule and the Hydrogen Molecule-Ion and Related Problems," *Chem. Rev.*, **1928**, *5*, 173-213.
29. Discussed by Pauling with John Heilbron, March 27, 1964, Pasadena, 2nd of 2 sessions, pp 15-16. Sources for the History of Quantum Physics (Berkeley depository).
30. Charles Coulson later claimed that the development of wave mechanics among physicists came to a "full stop" about 1929 insofar as chemistry was concerned; see M. J. Nye, *From Chemical Philosophy to Theoretical Chemistry: Dynamics of Matter and Dynamics of Disciplines 1800-1950*, University of California Press, Berkeley, CA, 1993, 239. On Coulson, see A. I. Simoes and K. Gavroglu, "Quantum Chemistry *qua* Applied Mathematics: The Contributions of Charles Alfred Coulson (1910-1974)," *Historical Studies in the Physical and Biological Sciences*, **1999**, *29*, 363-406.
31. See especially L. Pauling, "The Nature of the Chemical Bond. II. The One-Electron Bond and Three-Electron Bond," *J. Am. Chem. Soc.*, **1931**, *53*, 3225-3237; and L. Pauling and J. A. Sherman, "The Nature of the Chemical Bond. VII. The Calculation of Resonance Energy in Conjugated Systems," *J. Chem. Phys.*, **1933**, *1*, 679-686. See K. Gavroglu and A. Simoes, "The Americans, the Germans, and the Beginnings of Quantum Chemistry: The Confluence of Diverging Traditions," *Hist. Stud. Phys. Biol. Sci.*, **1994**, *25*, 47-110 (81). Pauling's 1931-1933 papers were incorporated into *The Nature of the Chemical Bond and the Structure of Molecules and Crystals: An Introduction to Modern Structural Chemistry*, Cornell University Press, Ithaca, NY, 1939.
32. W. N. Lipscomb, "Reflections," in R. S. Krishnamurthy *et al.*, Ed., *The Pauling Symposium: A Discourse on the Art of Biography*, Oregon State University Libraries Special Collections, Corvallis, 1996, 112-140 (117).
33. L. Pauling and E. B. Wilson, Jr., *Introduction to Quantum Mechanics With Applications to Chemistry*, McGraw-Hill, New York, 1935; Dover reprint edition, 1985, 1.
34. Quoted in Hager, Ref. 18, p 217.
35. E. Garfield, "Commentary in Tribute to Linus Pauling: A Citation Laureate," *The Scientist*, January 23, 1989, *3*, 10 (http://thescientist/com/yr1989/jan/opin2_890123.html).
36. L. Pauling and R. Hayward, *The Architecture of Molecules*, W. H. Freeman, San Francisco, CA, 1964, jacket. See M. J. Nye, "From Student to Teacher: Linus Pauling and the Reformulation of the Principles of Chemistry in the 1930s," in A. Lundgren and B. Bensaude-Vincent, Ed., *Communicating Chemistry: Textbooks and Their Audiences, 1789-1939*, Science History Publications, Canton, MA, 2000, 396-414. On the design of new high school sciences courses in post-Sputnik America using the CBA or Chemical Bond Approach, see L. R. Raber, "75 Years of Education: Changing Priorities Drive Progress in Education," *Chem. Eng. News*, **January 12, 1998**, *76*, 111-120 (117-118). On Otto T. Benfey's role in this movement, see J. J. Bohning, "From Stereochemistry to Social Responsibility: The Eclectic Life of Otto Theodor Benfey," *Bull. Hist. Chem.*, **1992-1993**, *13-14*, 4-16 (10-12).
37. E. Francoeur, "The Forgotten Tool: The Design and Use of Molecular Models," *Soc. St. Sci.*, **1997**, *27*, 7-40, notes 69, 79, and 87.
38. Ref. 37, p 23; D. Rouvray, "Model Answers?" *Chem. Br.*, **September 1999**, 30-32 (32); M. J. Nye, "Paper Tools and Molecular Architecture in the Chemistry of Linus Pauling," paper presented at Max Planck Institute for the History of Science, Conference organized by Ursula Klein, December 1999.
39. L. Pauling and L. O. Brockway, "Carbon-Carbon Bond Distances," *J. Am. Chem. Soc.*, **1937**, *59*, 1223-1236.
40. Ref. 37, pp 23-24.
41. Linus Pauling, letter of application to the Carnegie Institution, February 9, 1932; Puling Papers, OSU: LP

Science/14.022/folder 22.1; and L. Pauling, "The Division of Chemistry and Chemical Engineering at the California Institute of Technology: Its Present State and Its Future Prospects. August 15, 1944," typescript, Pauling Papers, OSU.
42. Ref. 37, p 28.
43. J. D. Watson, *The Double Helix*, G. S. Stent, Ed., W. W. Norton, New York, 1980, 34.
44. Hager, Ref. 18, p 375; Ref. 37: notes that the chemistry shop models used as tools in coming up with the alpha-helix structure were not mentioned in publications, with the exception of a later article in 1953 in *Review of Scientific Instruments*. See also M. Rouhi, "Tetrahedral Carbon Redux," *Chem. Eng. News*, **September 6, 1999**, *77*, 28-32, quote of Francoeur, p 30.
45. "Chemists Solve A Great Mystery," *Life*, September 24, 1951, 77.
46. Ref. 45, p 77.
47. Hager, Ref. 18, pp 306-307.
48. Ref. 47, p 339.
49. Ref. 47, pp 353-354, 390, 443, 466. See also J. D. Roberts, *The Right Place at the Right Time*, American Chemical Society, Washington, DC, 1990, 136-137, and "Assessing Pauling's Wide-Ranging Life," *Chem. Eng. News*, **April 22, 1996**, *74*, 47-49.
50. Other scientists addressing these issues included Barry Commoner at Washington University at St. Louis, George Leroy at the University of Chicago, and Warren Weaver, a former grant officer at the Rockefeller Foundation and president of the American Association for the Advancement of Science, who testified in Congress that H-bomb testing would cause physical defects in 6,000 babies in a year. See T. Goertzel and B. Goertzel, *Linus Pauling: A Life in Science and Politics*, Basic Books, New York, 1995, 143.
51. Quoted in L. Pauling, *No More War!*, Dodd, Mead & Co., New York, 1958, 119-120. See *Life*, February 10, 1958.
52. See *No More War!*, Ref. 51, pp 125-127. The debate is published in "Fallout and Disarmament: A Debate between Linus Pauling and Edward Teller," *Daedalus: The American National Style*, **Spring 1958**, *87*, 147-163. Thanks to Gerald Holton for a copy of the article.
53. Hager, Ref. 18, p 513.
54. A scientist at the national laboratory at Livermore later recalled that qualms rarely were voiced by scientists about the weapons research underway at Livermore except during the US-Soviet testing moratorium from 1958 to 1962, which was preceded by this national and international debate about the hazards of testing. H. Gusterson, *Nuclear Rites: A Weapons Laboratory at the End of the Cold War*, University of California Press, Berkeley, CA, 1998, 53. Both US and Soviet diplomats were beginning to suggest cutbacks in conventional weapons and a ban on nuclear testing as a first step toward disarmament. The Cuban missile crisis of 1962 moved both sides to a focused effort on achieving a Limited Test Ban Treaty in August 1963. See K.-H. Barth, "Science and Politics in Early Nuclear Test Ban Negotiations," *Physics Today*, **March 1998**, 34-39.
55. F. Catchpool, "Personal Reminiscences about Linus Pauling," in *The Pauling Symposium*, Ref. 32, pp 149-156 (155-156); Hager, Ref. 18, pp 549-550; and M. J. Nye, "What Price Politics? Scientists and Political Controversy," *Endeavour*, **1999**, *23*, 148-154.
56. See E. Richards, *Vitamin C and Cancer: Medicine or Politics?*, Macmillan Publishing, London, 1991.
57. On Mesmer: R. Darnton, *Mesmerism and the End of the Enlightenment in France*, Harvard University Press, Cambridge, MA, 1968.
58. Hager, Ref. 18, pp 577-578.
59. See L. Pauling, "The Revolutionary Age: The Challenge to Man," delivered at University of California at Irvine, March 3, 1968, Pauling Papers, OSU: LP Speeches/1968s.3. I am grateful to J. Christopher Jolly for this reference.
60. T. S. Kuhn, *The Structure of Scientific Revolutions*, 2nd ed., University of Chicago Press, Chicago, IL, 1970.
61. In 1954, the year that Pauling received the Nobel Prize in Chemistry, Pauling wrote Dennis Flanagan, the editor of *Scientific American*, that he and Corey had taken "the most important step forward that has been made during the last 15 years or perhaps 50 years in this field." Quoted in Hager, Ref. 18, p 377.
62. Raber, Ref. 36, pp 117-118.
63. See E. Francoeur, "Powerful Tinker Toys: Molecular Models and the Experimental Articulation of Structural Constraints," paper presented at Max Planck Institute for the History of Science, Conference organized by Ursula Klein, December 1999.
64. R. Hoffmann and R. B. Woodward, "Orbital Symmetry Control of Chemical Reactions," *Science*, **1970**, *167*, 825-831 (825).

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