Linus Pauling & Scientific Revolutions of the 20th Century

The Herbert H. Reynolds Lectureship in the History and Philosophy of Science

A lecture by Mary Jo Nye

Oregon State University

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Linus Pauling and Scientific Revolutions of the 20th Century

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Linus Pauling was one of the great revolutionary scientists of the 20th century. He played a formative role in five major developments in modern science: the application of quantum physics to chemistry; the use of theories of chemical structure in biology in the revolution we call molecular biology; the construction of molecular architecture and molecular models that are characteristic of modern chemistry; the development of what Pauling called "orthomolecular medicine" whereby diseases are results of molecules; and the emergence of the role of scientist as public citizen, both in influencing public opinion against nuclear testing and in advocating Vitamin C as low-cost cancer therapy.

The date of this afternoon's lecture falls midway between two important dates in the history of 20th century science and, indeed, between two dates which mark anniversary celebrations in 2003. The first date, February 28, was the anniversary of the birth of Linus Pauling in 1901 in Portland, Oregon, a date that is commemorated with a public event every year at Oregon State University, where Pauling took his undergraduate degree in chemical engineering in 1922. The second date, April 25, is the anniversary of the publication in the British journal *Nature* of the revolutionary paper by James Watson and Francis Crick on the molecular structure of DNA. This 50th anniversary of DNA in 2003 is an event that is being celebrated around the world from Sydney, Australia to Cold Spring Harbor in New York State to London and Cambridge in England, where the Royal Society and the University of Cambridge are among many institutions staging big events. A plaque on the wall of the Cambridge pub "The Eagle" will be unveiled in late April, marking the spot where Francis Crick triumphantly entered with Jim Watson at lunchtime on Feb. 28, 1953, "to tell everyone within hearing distance that we had found the secret of life." Improbably, Crick and Watson had arrived at the first correct model of the double helix on Pauling's birthday.

A great deal of the drama in the story of the "Discovery of the Double Helix," as James Watson told it in his autobiographical book of 1967, lay in what he, and later Crick, depicted as a mad pursuit of the DNA prize (meaning the Nobel Prize) and their headlong race against the more senior and legendarily charismatic figure of Linus Pauling. The second paragraph of their Nature paper pits Watson and Crick's model for DNA explicitly against Pauling's one-month-old model. Pauling and Robert Corey had proposed a structure, which had been made privately available to Watson and Crick, before publication, by none other than Pauling's son Peter, who was sharing an office with Watson and Crick at the Cavendish Laboratory at the time.

Pauling's incorrect DNA model consisted of three intertwined chains, with bases on the outside, and un-ionized phosphate groups on the inside. Watson and Crick recognized that the model was wrong, and that it would take hardly any time for Pauling to recognize the error of not giving electrical charge to the phosphate groups in an acid. A visit to the X-ray crystallography laboratory of Maurice Wilkins in London unexpectedly brought Rosalind Frankland's recent photographs of a new form of water-packed DNA into Watson's hands. He saw in her photograph the clear black cross image, which suggested a double helical structure.

The Watson and Crick "discovery," as they called it, became a legendary saga of Jack and the Beanstalk, or two Davids against Goliath, with Pauling in the role of Goliath. Certainly by 1953 Pauling had achieved the stature of a scientific giant. He would receive the Nobel Prize in Chemistry in 1954. He would also go on to receive a second Nobel Prize, becoming the only person in the history of the Nobel Foundation to receive two unshared Nobel awards. Pauling's second Prize would be the Peace Prize for 1962, for his role in the grassroots campaign to ban atmospheric testing of nuclear weapons. 1962 was also the year for which Crick, Watson, and Wilkins shared the Nobel Prize in Physiology or Medicine for their discoveries on the structure of DNA.

Pauling's was a revolutionary role in science, both because of the conceptual transformations he helped effect in three scientific disciplines: chemistry, molecular biology, and molecular medicine; and because of the political transformation he helped launch in the role of the scientist as public citizen.

What is meant by a "scientific revolution"? The term "scientific revolution" has its origin in characterizations in the early 18th century of the astronomy, mathematics, and mechanics of the previous 17th century. A "scientific revolution" came to be associated with the names of Copernicus, Galileo, and Newton. By the end of the 18th century, there was talk of a revolution that had occurred in chemistry, associated with the name of the French physical and bio-chemist Antoine Lavoisier. The Darwinian Revolution and Mendelian Revolution followed, as did the 20th century revolutions of quantum mechanics and relativity, marked by the names of Max Planck, Niels Bohr, Albert Einstein and others. Such revolutions all require the reconstruction of prior theory and the reevaluation of prior fact, a re-writing of textbooks, and a retooling of the laboratory or observatory. Accepted models, or paradigms, in the words of philosopher Thomas Kuhn, become inadequate or incommensurable with a new system of scientific explanation and practice.

Pauling, as we will see, may not have set out to initiate a revolution, but, like the youthful Lavoisier of the 1770s, Pauling in the 1920s aspired to participate in what he saw as revolutionary developments in the physics and chemistry of his time. The application of quantum mechanics to chemistry was an exciting new frontier, and Pauling was to become a giant figure in the construction of a new chemistry beyond the frontier. His intelligence was matched by extraordinary versatility and self-confidence, again like the young Lavoisier. Pauling ended his career in the public eye, suffering public opprobrium for the political implications of his views beyond the laboratory, although, unlike Lavoisier, Pauling was not forced to the guillotine.

The frontier spirit came naturally to Pauling, who grew up in the American West. He was born the son of a pharmacist, in Portland, Oregon, in 1901. His mother ran a boarding house. In January 1917 Pauling 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.

While preparing his first chemistry lectures in 1920, Pauling ran across papers in the Journal of American Chemistry on the structure of atoms and the new electron-particle theory of valence. These papers, by the American industrialist chemist Irving Langmuir, who would receive the Nobel Prize in 1932, led Pauling back to a paper on the chemical bond by G.N. Lewis, who taught at Berkeley, and whom Pauling admired for the rest of his life. Pauling became hooked, so to speak, on the chemical bond.

Pauling was ambitious early on. He applied for a Rhodes scholarship, which he did not receive, and like others among his 12 classmates in chemical engineering at Oregon Agricultural College, he applied to graduate school. In the fall of 1922 Pauling entered the California Institute of Technology where Arthur Noyes headed the chemistry department. By then Pauling had proposed marriage to Ava Helen Miller, a student in his chemistry class of the previous spring. His summer letters to Ava Helen give insights into the ambitions of this young chemical engineering graduate.

Not surprisingly, Pauling 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 if he might be a "second Noyes." At summer's end, Pauling wrote of his desire to live up to his ambitions and her expectations. He wrote that he aspired to [nothing other than] the Nobel Prize, "something which connotes a lifetime of unselfish effort, as does the Perkin's [sic] Medal."

After arriving at Caltech in fall 1922, Pauling's curriculum included up-to-date courses in thermodynamics, atomic structure, and dynamics. He studied kinetic theory with Caltech Nobel Prize laureate Robert Millikan, and he learned the new quantum theory from visiting Austrian theoretical physicist Paul Ehrenfest. He was ecstatic following his first meeting with the Physics and Astronomy Club in October 1922, writing Ava Helen 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 [Professor] Tolman and thus felt puffed up." Ambitious and conscious of his ambition, Pauling moved ahead in his studies.

His first paper appeared in 1923 on the X-ray crystallographic structure of the mineral molybdenite (MoS_2). In the next few years, Pauling authored or co-authored a dozen crystallography-structure publications. However, his 1926 application for a Guggenheim Foundation Fellowship focused on something different. Pauling expressed the aim to take up the German Professor Arnold Sommerfeld's challenge for

"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 and how this qualifies the atom to form molecules and to enter into chemical compounds." He wanted to take part in a revolutionary new reductionist and mathematical program for chemistry.

Returning in late 1927 from 18 months in Munich, Copenhagen, and Zurich, Pauling became an assistant professor at Caltech in theoretical chemistry. He had learned first-hand in Zurich of Walter Heitler and Fritz London's brand-new application of quantum-wave mechanics to the hydrogen molecule, using Heisenberg's notion of exchange energy, and in 1928, at the age of 27, Pauling began to sketch ideas for a theoretical treatment of chemical bonds for the simplest hydrocarbon molecule: methane.

By 1931, he had arrived at the notion of what he later called promotion of electron energy levels or hybridized electron orbitals in the carbon atom, so that he could explain the bonding of carbon atoms with other atoms using the still-novel idea of the electron as a wave phenomenon. He began writing a series of papers on "The Chemical Bond," feeling keen competition in a race to found a new theoretical chemistry with Harvard's John Slater and the University of Chicago's Robert Mulliken. Assessing Pauling's work of the early 1930s, Harvard University chemist and Nobel laureate William Lipscomb recently said that Pauling's first paper of 1931 simply "changed chemistry" forever.

The point was not only to change chemistry in principle, but in practice. With his junior colleague E. Bright Wilson, Jr., Pauling wrote the highly technical Introduction to Quantum Mechanics with Applications to Chemistry in 1935. Here they demonstrated 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." Pauling then wrote the less technical book, *The Nature of the Chemical Bond*, in 1939. Here he laid out in a largely non-mathematical way the new theory of the electron valence-bond, including the concepts of atomic orbital and of electronic resonance in molecules like benzene, which previously had been represented in terms of alternating single and double bonds, but now could better be understood mathematically rather than graphically.

Pauling's books changed the way scientists thought about chemistry, presenting chemistry as a disciplinary field unified by an underlying theory and demonstrating how the characteristics of the chemical bond determined the structure of molecules, and how the structure of molecules determined molecular properties. The founder of the Science Citation Index, Eugene Garfield, noted in 1989, the 50th anniversary year of publication of the book *The Chemical Bond*, that it ranked in the top 10 scientific publications cited since 1945. In 1988 alone, *The Chemical Bond* received over 600 citations, 50 years after its publication. As Cambridge biochemist Max Perutz put it, Pauling had shown "that chemistry could be understood rather than being memorized."'

After *The Chemical Bond*, Pauling radically restructured the format for teaching general chemistry to college undergraduates. By the 1949-1950 academic year, his textbook *General Chemistry* was selling 9,000 copies and it was regarded as a revolutionary textbook teaching students about the most current developments of chemistry.The book relaid the foundations of chemistry by beginning with electron theory, rather than with chemical elements and atomic weights. The textbook also 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.

Pauling's visual intuition not only transformed chemical teaching by the 1950s, but it also transformed chemical research. For his lectures, Pauling directed Caltech shop assistants to design and make wooden and plastic balls of different colors, their scales and shapes representing carbon, oxygen, and nitrogen atoms. Of course, these kinds of models were not new to chemistry. Ball and stick models had made their first appearance around 1810 in John Dalton's sets of wooden balls and sticks in Manchester, England. However, Pauling's models were different from the 19th century versions in that he had reliable physical estimates of atomic sizes, interatomic distances in molecules, and bond angles in molecules, based in X-ray and electron-diffraction experiments and in machine-calculated equations.

In 1938 Pauling began corresponding with Joseph Hirschfelder at

Wisconsin about the usefulness of new kinds of three-dimensional molecular models: the so-called "space-filling" models.The German chemist H.A. Stuart had begun designing these in 1934, with spherical atom units that are brought into contact with each other and that have diameters roughly proportional to their calculated Van der Waals radii. The first space-filling models were marketed by a German firm but were expensive to purchase, so Hirschfelder began constructing his own, first from cork and then from plaster of paris, corresponding with Pauling about diameters to be used for the atom. By 1939 the Fischer Scientific Company was selling kits of the models. Following the war, Pauling oriented his laboratory toward making space-filling models as tools for the study of structures of polypeptides, proteins, and other biologically interesting organic molecules. These models were not cheap. Indeed, as reported to the Rockefeller Foundation in a proposal for support of research costs, it was noted that a single turn of a custom-made DNA double helix came to cost several thousand dollars to construct.

Like many chemists, Pauling found himself in a university institution in which biology and medicine increasingly were gaining attention. At Caltech, this orientation began in the early 1930s after Thomas Hunt Morgan was recruited from Columbia University to organize a biology division. Pauling began to participate in the Tuesday afternoon biology seminars, and, as he later put it, "I began to become familiar with biological problems, and to think about possible ways in which biological specificity could be explained in terms of interactions between molecules." Reading about biology had immediate results for Pauling's thinking about chemical bonds, so that what he had called "changed quantization" of orbitals in 1931 became "orbital hybridization" by the late 1930s. Biologically significant compounds like urea, oxamide, and oxamic acid were among the compounds that Pauling and his associates were investigating, and Sherman and Pauling were calculating resonance energies for the nucleic-acid bases guanine and purine in 1933.

A shift in emphasis in funding priorities at the Rockefeller Foundation influenced Pauling's research agenda. A note among Pauling's papers makes the situation clear:

Warren Weaver suggests sending in a request for extension of the fund...He says their policy is to support a definite biological program* (*especially quantitative work in biology). Atomic physics is definitely out. My work may be included because of its bearing on biological problems, although ordinarily work in organic chemistry would not be.

This biologically oriented work resulted in research on oxygen and hemoglobin in 1935, including the magnetic properties of the hemoglobin molecule. Then with Alfred Mirsky from the Rockefeller Institute, Pauling turned to protein structure, which was a now front-line subject for structure determination using X-ray crystallography in Berlin, London, and Cambridge. Influenced partly by the work of Hermann Mark in Berlin, Pauling and Mirsky proposed a coiled, or folded, structure for protein. They also provided a long argument that proteins are molecules at a time when the colloidal theory of proteins was losing its popularity, but was not yet dead.

In 1936, while on a short visit to the Rockefeller Institute in New York, Pauling was asked by Karl Landsteiner how to explain the observed properties of antibodies and antigens by means of molecular structure. By 1940, Pauling and his Caltech colleague Max Delbrück provided a possible answer to Landsteiner's question: the specific combining region of an antibody molecule might be complementary in structure to a portion of the surface of the antigen. It was well established that optical isomers of a molecule differ in their biological activity. Pauling and Delbrück now asserted the significance of the exact size and shape of biological molecules, or of lock-and-key forms. They suggested, too, that biological replication was likely a matter of complementary shapes.

An example of the correlation of molecular shape with biological function followed in Pauling's work with Harvey Itano on sickle-cell anemia in the late 1940s. Pauling visualized the formation of self-complementary structures where "one end of the molecule is able to form a bond with the opposite end of another hemoglobin molecule. Under these circumstances the molecules clamp onto one another, so that red blood cells are twisted out of shape." Pauling coined the term "molecular disease" for sickle-cell anemia, as he increasingly oriented his work

toward chemical biology, molecular biology, and what Pauling called molecular medicine.

In 1948, while visiting at Oxford, Pauling found that many crystallographers were looking for evidence of spirals or helices in the structure of starches, insulin, and protein. Protein research was hot, and Lawrence Bragg's Cavendish Laboratory, led by biochemists John Kendrew and Max Perutz, was in pursuit of protein structure. While home at his Oxford flat with the flu, Pauling amused himself by modeling the protein keratin as a spiral, using paper, ruler and pencil to sketch out a chain of amino acids, and drawing the atomic-bond lengths and angles from memory. He turned the paper chain into a spiral, but his initial enthusiasm flagged as he realized that the likely X-ray pattern produced from his model would not match the X-ray patterns that William Astbury had been getting, with strong reflection at 5.1 Angstroms, thought to be the basic repeat unit along the length of the chain. In contrast, Pauling's repeat unit was 3.7. Pauling showed friends his paper models at his Oxford flat, but he had to await his return to Caltech to follow up with more sophisticated resources.

After further work in Pasadena, Pauling and Corey published two proposed structures for the keratin "alpha helix," as they called it, one with 3.7 amino acid residues per turn and the other at Astbury's 5.1. To their delight, the fiber manufacturing firm of Courtaulds in London confirmed the 3.7 reflection (but not the 5.1).

One of Pauling's Caltech colleagues, the biologist Ray Owen, later recalled how news circulated at Caltech in the winter of 1951 that Pauling's team was constructing protein models precise to the finest details. When Pauling was scheduled to give a seminar to the biology division, the large lecture room at was packed. Pauling did not disappoint his audience, entering the 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:

> [Pauling] 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, taking a jackknife from his pocket and opening it, reaching for the

string...when he had had enough fun, Pauling 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.

Pauling's performance was the talk of Pasadena and the world. Jim Watson heard the entire account in Geneva while visiting Jean Weigle, who was just back from a winter term at Caltech.

On his 50th birthday, Pauling mailed a manuscript to the National Academy of Sciences, co-authored with Corey and Harvey Branson, on the structure of proteins. Two months later, Pauling and Corey followed with a set of seven papers which dominated the May issue of the National Academy's *Proceedings*, including the structure of collagen, modeled as three helixes twisted around each other to form a single cable. Pauling wrote Dennis Flanagan, the editor of *Scientific American* that he and Corey had solved the protein structure, bragging that this is "the most important step forward that has been made during the last...50 years in this field."

This statement was not far wrong. The protein work was revolutionary. Jim Watson had first met Pauling in the summer of 1949 when Watson worked with Delbrück for a few months in Pasadena. When Watson first met Crick at Cambridge, he wrote Delbrück that Crick was "no doubt the brightest person I have ever worked with and the nearest approach to Pauling I've ever seen...He never stops talking or thinking." "The key to Linus' success," Watson wrote in 1968, "...was his reliance on the simple laws of structural chemistry. The alpha-helix had not been found by only staring at X-ray pictures; the essential trick, instead, was to ask which atoms like to sit next to each other. In place of pencil and paper, the main working tools were a set of molecular models superficially resembling the toys of preschool children. We could thus see no reason why we should not solve DNA in the same way."

And so they did, by their own cleverness and the good fortune of Watson's access to photographs taken by Rosalind Franklin in Wilkins's laboratory at King's College in London. As mentioned earlier, Pauling

and Corey published a paper in February of 1953 modeling DNA with three intertwined chains having phosphates near the fiber axis and bases on the outside. They based this structure on what turned out to be misleading photographs of what they did not know was a mixture of two forms of DNA. In April, using Franklin's photograph of the pure B form of DNA, Watson and Crick published a structure of two helical chains, each coiled round the same axis, with bases on the inside of the helix and phosphates on the outside. Asked over and over again how he could have made his mistake, Pauling later reminisced:

> In hindsight, it is evident that I made a mistake on Nov. 26, 1952, in having decided to study the triple helix rather than the double helix...I had not forgotten that Delbrück and I had suggested that the gene might consist of two complementary molecules but for some reason, not clear to me now, the triple chain structure apparently appealed to me...I cannot say what would have happened if I had...succeeded in getting access to the diffraction photographs of DNA...There is no doubt that even rather simple ideas sometimes are very elusive.

Thus, Pauling was gracious in defeat. The issue of Franklin's X-ray photographs is a much-vexed one, not only because of Watson's use of her data, but because Pauling was prevented by the U.S. State Department from making a trip to England in the fall of 1952, just before he began modeling DNA. This brings us to the impact upon Pauling's scientific work and scientific reputation of his role as a public citizen.

Pauling had remained in Pasadena during the Second World War. Once it was over, Pauling, like many scientific colleagues both inside and outside the Manhattan Project, joined organizations concerned about atomic-science and atomic bomb issues. He gave invited lectures to local Los Angeles groups, explaining the way an atomic bomb works and criticizing the Truman Administration's talk of a first nuclear strike against the Soviet Union.

In late 1947, an anonymous member of the American Chemical Society contacted the FBI with worries about the political views of the Society's new president-elect. In 1948, while Pauling was on his visiting appointment in Oxford, FBI agents quizzed co-workers, neighbors, and

Caltech administrators, looking through his Caltech personnel file to detect any signs that he was a Communist sympathizer.

Cleared of any wrongdoing by a Caltech committee in December 1950, Pauling was denied a U.S. passport in fall 1952, preventing him from attending a Royal Society discussion on proteins. He had intended to talk with Maurice Wilkins personally in London about the King's College X-ray diffraction photographs. Pauling's passport was restored, and then denied again. When reports came out in spring 1954 of radiation poisoning of Japanese fishermen, following the U.S. explosion of a hydrogen bomb at Bikini Atoll, Pauling connected the problem of radiation poisoning and possible genetic damage from fallout to his own recent research interests in DNA and nucleic acids as carriers of inherited characteristics, including mutations in genes. He began spending half his time reading, talking and writing about bombs and fallout.

Pauling's activities included writing two papers on probabilities of genetic mutations from radionuclides in atmospheric fallout. The Atomic Energy Commission had set up monitoring programs for strontium-90 in 1949, concluding that it might pose a hazard because of the isotope's ability to enter the food chain, since strontium is similar chemically to calcium. An Argonne Laboratory scientist (Miriam Finkel) published a paper in Science in 1958 with the memorable title "Mice, Men and Fallout," in which she concluded that strontium-90 contamination was "extremely unlikely to induce even one bone tumor or one case of leukemia." Pauling, adopting the less optimistic hypothesis of his Caltech genetics colleague E. B. Lewis on minimum levels of radiation triggering genetic damage, marshaled arguments against Finkel,which got coverage in *The New York Times*, along with Pauling's earlier paper on the genetic effects of the radionuclide carbon-14.

The fallout issue was an important factor in scientists' renewed activism in the mid-1950s in support of disarmament. Bertrand Russell and Albert Einstein co-authored a manifesto, Einstein's last before his death, which was signed by Pauling and 10 other scientists. It led to the first Conference on Science and World Affairs at the village of Pugwash in Nova Scotia in the summer of 1957. Joseph Rotblatt, one of the founders, received the Nobel Peace Prize in 1995, along with the Pugwash organization.

Pauling's 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." Teller and Pauling debated each other in live coverage on KQED television in San Francisco, with no clear resolution of technical issues for viewers. 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.

In the fall of 1963, it was announced that Linus Pauling would receive the 1962 Nobel Peace Prize, following the signing in August 1963 of the limited test ban treaty. *Life* magazine carried the extraordinary headline "A Weird Insult from Norway," stating that the limited test-ban treaty had nothing whatsoever to do with Pauling or the 1958 petition to the U.N. 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. The American Chemical Society mentioned the peace prize only in a single paragraph in the back pages of an issue. Pauling resigned from Caltech and from the American Chemical Society.

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, a cure for cancer.Pauling's interest in genetic mutations had led him to calculations of the natural evolutionary rates of change in protein and DNA (the "evolutionary clock"), and then to researches on molecular strategies to combat molecular diseases (the campaign for Vitamin C). Pauling's hypothesis about the merits of vitamins and other antioxidants in the treatment of cancer soon embroiled him with members of the Mayo Clinic and the broader medical community.

With his now customary self-confidence and moral fervor, Pauling extended the debate beyond the laboratory and the clinic to the public airways, charging that his Vitamin C opponents were self-interested and feared "the monetary losses that would be inflicted on pharmaceutical manufacturers, professional journals, and doctors themselves" if the value of Vitamin C therapy were admitted. Pauling now spoke of a "revolutionary age" and challenged his peers that "scientists must be radicals, not conservatives" in their service to humanity. Nor is his crusade forgotten. A full-page advertisement in the Feb. 2, 2003 *New York Times*, taken out by Dr. Matthias Rath, prominently displays a photograph of Rath with Pauling under the heading "Make Health — Not War!"

By the 1980s, Pauling's public crusades had largely discredited him in some professional and political circles. But, by the time of his death in 1994, the rancor had abated, even as scientists' involvement in public-interest groups also had increased. In 1998, the American Chemical Society's weekly journal the *Chemical and Engineering News* 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. The result was a list of more than 1,200 individuals, giving a top-75 group. Pauling's name was at the top of the list.

Some 25 years earlier, in 1975, a different kind of poll was taken by the British journals *New Scientist* and *New Society*. That poll sought to assess readers' images and stereotypes of scientists by asking an open-ended question such as "When I think of a scientist, I think of...," as well as making statements intended to elicit agreement or disagreement from readers, such as "scientists are respected by the public." The British poll received approximately 1,600 responses, of which fewer than 10% (119) came from professional chemists. Pauling's was the 15th most cited, among names which included Darwin and Einstein, Galileo, Newton, Pasteur, and, among contemporary scientists, as polled among a British readership, Jacob Bronowski, Fred Hoyle, and Peter Medawar. Bronowski, Hoyle, and Medawar had enjoyed, or suffered, considerable media attention in the 1960s and early 1970s. In contrast, the *Chemical and Engineering News* poll more clearly reflects judgments by Pauling's professional peers in the field of chemistry. He simply was regarded as the most important chemist of the century.

Like that great figure of the 18th century chemical revolution, Antoine Lavoisier, Pauling's work ranged broadly across physics and

chemistry, chemical and physical methods, mathematical and visual explanations, biological and physical chemistry. Thomas Kuhn marks a scientific revolution by the invention of new theories, new languages, and new textbooks, replacing the old way of seeing things. Pauling revolutionized the principles and the pedagogy of chemistry with a new language, new representations, and new textbooks. His *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 in the chemical bond approach (CBA). The CPK, or Corey-Pauling Space Filling Models with Improved Koltun Connectors, became as common in chemical classrooms and laboratories as the periodic table. As Nobel laureates Roald Hoffmann and Robert Woodward wrote in 1970, a "revolution" 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 chemical reaction." This revolution created the molecular biology of DNA and of proteins, and it established a new discipline of "molecular medicine."

Like Lavoisier, Pauling's identity as revolutionary, or rule breaking scientist, also rests in the broader national and political context of his times, as he stepped out of the laboratory and into the public arena, at some cost to personal peace of mind and reputation. Pauling's crusades for Vitamin C challenged the medical establishment's reliance on pharmaceutical drugs and high-technology instrumentation. Similarly, his arguments on genetic damage from radioactive fallout challenged the reassurances given by governmental agencies that nuclear testing could do no harm. The public-citizen groups that Pauling helped mobilize in the 1950s would end up focusing not only on nuclear testing, but also on wider sources of environmental pollution and degradation in a new environmental movement. Rachel Carson's *Silent Spring* begins with a reference to Strontium-90.

Pauling's role as a scientist and Pauling's persona as charismatic and dazzling scientist-about-town was not unlike Albert Einstein's. This comparison is hardly coincidental, since Albert Einstein was one of Pauling's personal heroes. Like Einstein, Pauling in his scientific work took delight in crossing boundaries and frontiers, and in confounding and even scandalizing his peers and colleagues. Pauling admired

Einstein's iconoclastic intellect, as well as Einstein's charismatic style. Pauling also admired the moral courage and outspoken dissent that Einstein demonstrated in both Europe and North America throughout Einstein's lifetime in the limelight. Neither Einstein nor Pauling lived tranquil lives, but they chose to become and remain public figures. Pauling in his beret, like Einstein on a bicycle, or Einstein with his tongue stuck out, has become an icon of 20th century science and of revolutionary science in the 20th century.

Acknowledgements and Notes

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