LINUS PAULING
Selected Scientific Papers

VOLUME I
Physical Sciences
WORLD SCIENTIFIC SERIES IN 20TH CENTURY CHEMISTRY

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Linus Pauling is widely considered to be the most influential chemist of the 20th century and one of the greatest scientists of all time. He made important contributions over an enormously broad range of scientific subjects, including quantum chemistry, structural chemistry, structural crystallography, mineralogy, biochemistry, molecular biology, molecular medicine, and biological evolution. For his research into the nature of the chemical bond and its application to the structures of complex substances he was awarded the Nobel Prize in Chemistry for 1954. This research changed the science of chemistry in a fundamental way, and later the science of biology as well. In 1963 he was awarded the Nobel Peace Prize for his work striving to eliminate the possibility of nuclear war. He is the only person ever to receive two unshared Nobel Prizes. He became widely known also for his public advocacy of the nutritional benefits of large doses of vitamin C and other vitamins. He died in 1994 at the age of 93.

When I came to Caltech in 1976, there was one name which, in my mind, is to chemistry what the Great Pyramid of Cheops (Khufu) is to the world. That name was Pauling. Caltech had a great pharaoh of chemistry, with a dynasty spanning over forty years. It was at Caltech where Linus made his major contributions to chemistry—especially the nature of the chemical bond, elucidating the concepts of hybridization, resonance, and electronegativity from studies of numerous crystal and molecular structures by x-ray and electron diffraction. His major contributions to biology included the $\alpha$-helix structure of polypeptide molecules and the concept of molecular disease. Caltech was the mecca of molecular structure. While there was a strained period at the time he left Caltech in 1964, Linus told me on several occasions of his highest admiration for the California Institute of Technology. This respect is mutual. Linus Pauling will always be remembered as one of the most distinguished members of our faculty, for his science, teaching, and leadership. Jack Dunitz puts it well when he says (in Chapter 18): "his name will be remembered as long as there is a science of chemistry." I might add biology too!
The present two-volume work is an anthology of Linus Pauling's most significant and influential scientific papers. The volumes are testimony to the extraordinary contributions of this giant and to his impact. They enable the reader to see in exact facsimile many of the original works upon which his fame as a scientist rests. These works represent a monumental contribution—a must for chemists, biologists, and scientists in general who want to understand the roots of important concepts in modern science, the foundations for which were laid down by Linus Pauling.

We are indebted to the Pauling family for preparing this anthology, and to World Scientific Publishing Company for accepting my initial suggestion that such an anthology be published. It will help assure that the scientific work of Linus Pauling is well preserved and available, and that this work, like the Great Pyramid, is not forgotten!

Ahmed H. Zewail
Linus Pauling Professor of Chemistry and Physics
California Institute of Technology
May 15, 1999
Preface

Shortly before his death on 19 August 1994 at his home on the California coast, Professor Linus Pauling was contacted by World Scientific Publishing Company with the proposal that the Company republish in book form a selection of his scientific writings. He agreed and his four children agreed to act as editors. The editorial process of selecting and assembling the papers to be included had, however, only just begun at the time of his death. The task of studying and considering the more than 1000 publications and selecting a limited number from this wealth of material was daunting. Pauling is reported to have said “the selection is easy—print them all.” But World Scientific wanted a more selective approach that would concentrate on the more important papers and avoid escalating the price out of reach.

With the family in mourning, the project languished for a time despite encouragement from admirers of Pauling and his scientific work. It was restarted by Barclay Kamb, who took on the job of Editor-in-Chief and moved the project forward to completion, albeit with many delays. (Barclay Kamb is Pauling’s son-in-law, colleague, former Ph.D. student, and Caltech professor of geology and geophysics.)

Editorial functions in the preparation of this work were as follows: son Peter Pauling Ph.D. was Editor of Part I (see General Introduction), grandson Alexander (Sasha) Kamb Ph.D. was Editor of Part III, son Linus Pauling Jr. M.D. was Editor of Part IV, daughter Linda Pauling Kamb B.A. was Editor of photographic illustrations and curator of the original publications, and Barclay Kamb Ph.D. was Editor of Part II, author of the General Introduction, and Chief Editor and coordinator of all components. The Editor of each Part had responsibility for the selection of papers for inclusion in his Part and wrote the Introduction for that Part. The final selection and the editing of the Introductions were done by the Chief Editor. Linda Kamb chose the photographs (mostly from her own collection), helped write the captions for them, and carried out the arduous search for original offprints of the selected papers. (Sadly, son Crellin Pauling Ph.D. could not contribute to the completion of the project, dying aged 60 on 27 July 1997.)
In view of the Editors' limited knowledge of the many scientific fields in which Linus Pauling worked and published, several specialists in various fields were asked to serve as Advisors for the selection of papers and in some cases to help with the writing of the introductions to the Parts. The Advisors were:

Prof. Jack D. Dunitz Ph.D., F.R.S., Professor of Chemistry, Eidgenössische Technische Hochschule, Zürich, Switzerland

Dr. Justine Garvey Ph.D., Visiting Associate, Division of Biology, California Institute of Technology, Pasadena, California

Dr. Zelek Herman Ph.D., Senior Research Scientist, Linus Pauling Institute of Science and Medicine, Palo Alto, California

Dr. Richard Marsh Ph.D., Senior Research Associate Emeritus, Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, California

Prof. Harden McConnell Ph.D., Professor of Chemistry, Stanford University, Stanford, California

Mrs. Dorothy Munro, Assistant to Linus Pauling, Linus Pauling Institute of Science and Medicine, Palo Alto, California

Prof. Ray Owen Ph.D., Professor of Biology Emeritus, California Institute of Technology, Pasadena, California

Prof. Alexander Rich M.D., Professor of Biology, Massachusetts Institute of Technology, Cambridge, Massachusetts

Prof. Verner Schomaker Ph.D., Professor of Chemistry Emeritus, University of Washington, Seattle, Washington (deceased)

Prof. Ahmed Zewail Ph.D., The Linus Pauling Professor of Chemistry, California Institute of Technology, Pasadena, California

The Editors express their sincere thanks to the Advisors for their invaluable help. They thank Professor Jack Dunitz for contributing the biographical memoir of Linus Pauling that he wrote originally for the Royal Society of London.

Our thanks go also to the Caltech photo lab (Richard Gomez) for much help in preparing the photographic illustrations for this work, to Ramesh Krishnamurthy of Special Collections, Oregon State University, for providing many of the original offprints, and to Kathy Lima, Denise Darrell and Anthony Pauling Kamb for word and data processing.
An American chemist came through University College London to visit me perhaps 30 years ago and mentioned a discussion with a graduate student. The subject may have been “hybrid bond orbitals” or “resonance” but it does not matter. The student said that the nature of the chemical bond came from Genesis. My visitor said: It did not; it came from Linus Pauling. In 70 years young chemists have forgotten from where the ideas, knowledge, and methods came. The Editors and Advisors hope that this republication will not only be a recollection but will also be a valuable asset in the education of scientists.

My view of Linus Pauling is necessarily different to that of others. For one thing, there is genetics, although my view of genetics is Thomas Hunt Morgan and fruit flies, and the Caltech maize genetics farm. For another, we were thrown into each other’s company by force of logistic circumstances from 10 February 1931 until 1952 when I left home. The “bond” and communication (“resonance”) grew stronger and stronger until 19 August 1994.

Peter Jeffress Pauling
Abergwenlais Mill
Wales, UK
14 December 1998
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GENERAL INTRODUCTION

Linus Pauling's published writings number some 1200 in all, of which about 850 are scientific papers and books, produced over the period 1923–1994. In the present pair of volumes, we the editors endeavor to place before you a substantial selection of Pauling's published contributions to science, reproduced from the original publications. Within the scope of some 1400 pages the selection aims to present Pauling's most important and influential scientific papers and the papers that best convey his imaginative style of scientific thinking and the considerable gamut of scientific subjects that he tackled. His writings on subjects outside the scope of science—on social, humanitarian, and political subjects—are presented in the book Linus Pauling in His Own Words, edited by Barbara Marinacci (1995), and in Linus Pauling on Peace, by Marinacci and Krishnamurthy (1998). The biographies by Thomas Hager (1995, 1998) and by Ted and Ben Goertzel (1995) provide detailed background material on Pauling's life and the context of his writings.

The selected scientific papers, listed in tables of contents, as explained below, are organized into four major subject groupings, designated Parts I to IV. Part I contains papers on the nature of the chemical bond, the subject for which Pauling was first and foremost acclaimed in the scientific world and for which he was awarded the Nobel Prize for Chemistry in 1954. (His second Nobel Prize, for Peace, awarded in 1963, relates to his writings in the social, humanitarian, and political areas mentioned above.) Part II contains papers on the atomic structure of molecules and crystals, which provided much of the observational evidence on which Pauling's concepts of the chemical bond in Part I were based. Part II also contains papers in which the principles of quantum mechanics, which provided the theoretical basis for many of Pauling's concepts of the chemical bond in Part I, were applied by him to understand the physical properties of molecules and crystals. The pervasive role of quantum mechanics, which was developed by physicists in the 1920's, during the early years of Pauling's career, makes somewhat blurry the distinction between the subject matter of Parts I and II, but the papers in Part I concentrate on conceptual and theoretical aspects of chemical bonding while the concentration in Part II is on observational and empirical evidence and on physical properties as distinct from
chemical bonding. Part III contains a major new thrust in Pauling’s research that began to develop in the late 30’s and culminated in the 50’s—the structure and function of large molecules of biological importance, particularly proteins. The bridge to Part III was the application of concepts and observational methods of Parts I and II to small organic molecules that are building blocks for the large molecules of biological importance. Finally, Part IV contains papers on biomedical subjects, beginning with Pauling’s much-cited 1949 discovery of molecular disease, which is considered by biologists and medical scientists to be among his greatest and most influential contributions to science. Part IV includes papers on nutritional (orthomolecular) medicine, which was the focus of much of Pauling’s research effort in his later years. Parts I and II are in Volume I of this two-volume anthology, and Parts III and IV are in Volume II.

To provide a sharper guide to the different subject areas of Pauling’s scientific research and writing, beyond the rather broad division into Parts I to IV, the 144 selected papers are further subdivided into seventeen chapters. Each chapter begins with a table of contents listing the selected papers contained in that chapter. This is followed by the actual papers, reproduced in exact facsimile from the original publications indicated by the citations in the table of contents. (In these citations, the by-line is omitted for single-author papers by Pauling.) The selected papers are presented in an arbitrary sequence that is primarily subject-matter oriented and secondarily chronological. The significance of the subdivision into chapters is briefly explained and the relationships between the chapters are discussed in an introduction at the beginning of each Part. Particularly important papers are noted but it is beyond the scope of the introductions to discuss each paper. However, we hope that the commentary provided will make the individual papers sufficiently self-explanatory by indicating their context.

The papers were selected from the list of Pauling’s scientific publications given in Appendix III, which is derived from a complete list of Pauling’s publications prepared by Z. S. Herman and D. B. Munro (1996) as noted below. The basis for selection is the editors’ judgement as to the scientific interest and importance of each paper and its representativeness for papers in its subject area, in relation to an overall limitation on the number of pages. A few selections were made to display collaborative work with students or more senior colleagues. In subject areas of the most importance, such as the nature of the chemical bond, the structure and function of proteins, and molecular disease, the selected papers constitute a substantial fraction of Pauling’s published papers in these subject areas, whereas in other areas, the selected fraction is smaller. We have tried to select representative papers from all scientific areas that Pauling was interested in and wrote about, but in some cases, interesting papers could not be included for lack of space. The selection was made with the help of a number of advisors, acknowledged in the Preface.
We have included only four selections from Pauling's several books, because it would be impractical to include more within the space limitation and because our main objective is to document Pauling's science as it emerged and first impacted the scientific world rather than as it appeared in later retrospectives. Two selections are from Pauling's *The Nature of the Chemical Bond*, which has been called the twentieth century's most important book in chemistry (for example, it was cited 16,027 times in the period 1955–1983). The third is a passage from Pauling and Wilson's *Introduction to Quantum Mechanics*, which has trained generations of quantum chemists and is said to be the longest-lived quantum-mechanics textbook in terms of length of time in print. The fourth book selection is a concluding summary from Cameron and Pauling's book on vitamin C and cancer. In a few cases we have included retrospective papers, which are placed at the end of the appropriate chapters, except for the 1954 Nobel Lecture, which is placed at the beginning of Chapter 1 where it provides an introductory overview of Pauling's contributions to the nature of the chemical bond. Many more of his retrospective scientific writings are presented and discussed in *Linus Pauling in His Own Words*, edited by Barbara Marinacci (1995).

Except for *Introduction to Quantum Mechanics*, we have likewise not included selections from Pauling's several textbooks, beginning in 1930 with *The Structure of Line Spectra* (with Samuel Goudsmit) and blossoming fully in 1947 with *General Chemistry*, an introductory textbook that for the first time presented chemistry in the light of chemical bonding theory and was widely influential in the teaching of chemistry at the first-year university level. Pauling was a charismatic and spell-binding teacher and lecturer. The scope of the anthology does not include Pauling's teaching, but hints of it will be found in the photographic illustrations (explained below).

Included as a final chapter (Part V, Chapter 18) is a compact, science-oriented biography "Linus Carl Pauling" from the *Biographical Memoirs of Fellows of the Royal Society of London* by Jack D. Dunitz (1996). This work summarizes Pauling's contributions to science and assesses their significance and impact, as judged by a leading structural chemist who knew Pauling well. It thus provides a frame of reference in which the original papers in this anthology can be studied and evaluated retrospectively. It also places Pauling's scientific work in the broader context of his life as a whole.

The selected papers in the present anthology are numbered from SP 1 to SP 144 in the somewhat arbitrary sequence in which they are presented. Throughout the two volumes the selected papers are identified by "Selected Paper number", with the prefix "SP". The SP designation is used to forestall confusion between the SP numbers used in the main text and the other numbers used in Chapter 18 (the Biographical Memoir) and in the appendices. Appendix I is a conversion table between the SP