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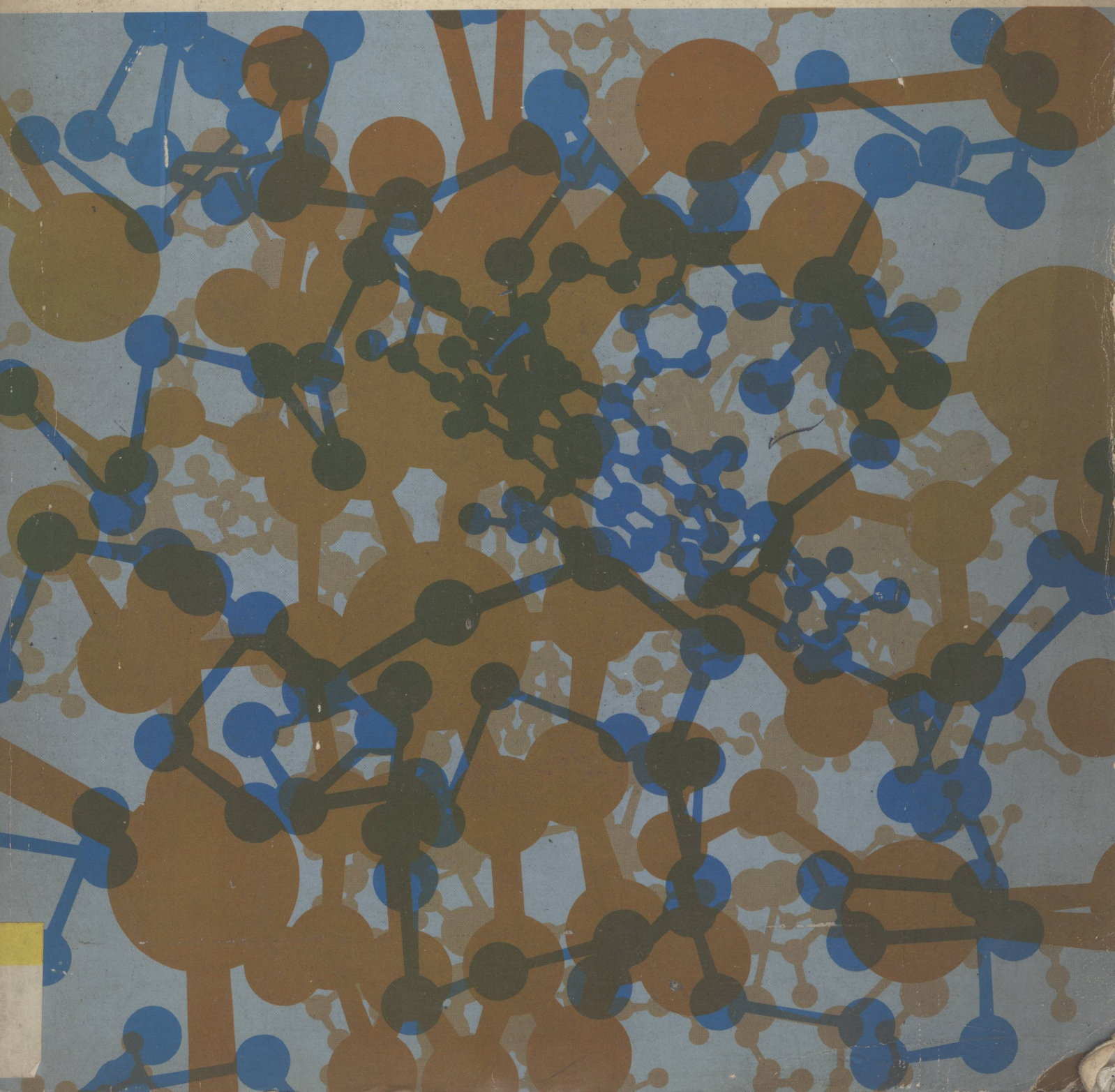
With Introductions by
JAMES B. IFFT
and
JOHN E. HEARST

General Chemistry



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SCIENTIFIC AMERICAN

GENERAL CHEMISTRY

with introductions by

James B. Ifft

University of Redlands

John E. Hearst

University of California, Berkeley

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GENERAL CHEMISTRY

PREFACE

This reader is designed to be a supplement to an introductory course in general chemistry. General chemistry courses are undergoing major changes at present, and this is reflected in the content of the reader. There are two basic reasons for these changes. First, college education has become the privilege of a far greater number of high-school graduates than were able to enter college a mere quarter-century ago. Furthermore, at the University of California, Berkeley, for example, about forty percent of these undergraduates enroll in a general chemistry course. A very small fraction of these students are destined to major in physical science or engineering. Therefore, we interpret this increase in enrollment as an indication that science is being studied because it is intrinsically interesting. This brings us to the second reason for the changes that are occurring in general chemistry courses, for there is no legitimate reason why this intrinsic interest should not be exploited and encouraged in the process of teaching chemistry. Because so many students today arrive in college with an interest in themselves and in their society, examples of chemistry from biology or ecology are stimulating to them. Evolutionary changes in curricula are not new, of course, for the curricula in universities have always been designed to be sensitive to the interests of that society to which the universities belong.

Scientific American is an excellent source for literature about the changing interests in science, for its success as a magazine depends on attracting an audience more general than the professional scientists whose opinions and interests dominate the professional science literature. Nevertheless, when we first conceived the idea of this reader, we were concerned that the relation between the subject matter of the typical general chemistry course and past *Scientific American* articles would not be sufficiently apparent to make the reader possible. We were pleasantly surprised to find a wealth of pertinent material that required no prior knowledge of the subject, material written in sufficiently simple language to provide source material for general chemistry. That so much of the material is related to biology as well is not a matter of our design so much as a reflection of the main interests of this period in scientific research.

Our reader has eight sections. The first section contains two articles, one by Linus Pauling entitled "Chemistry" and the other by George Wald entitled "The Origin of Life." These are designed to provide the definitions for chemistry and the limits of phenomena which are normally called chemistry. The second section deals with the atomic hypothesis, atomic structure, the periodic table and the elements, and the chemical bond. Section III deals with molecular structure from a very biological point of view, but nevertheless provides examples of molecular geometry, electronic excitation by light, chemical change induced by light absorption, biological specificity resulting from complex and detailed molecular structure, and the forces between molecules. The last of these examples is provided by a study of the cell membrane, which is an example of the behavior of polar and nonpolar

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chemical groups in water. Section IV provides a computer simulation of the motion of molecules in gases, liquids, and solids, and discusses crystal structure, electrical conductivity, transistors, and lattice dislocation. Ice provides an example of the nature of the hydrogen bond and an introduction to the notion of disorder or entropy. Section V deals with thermodynamics, kinetics, equilibrium, and oxidation-reduction. Section VI provides a description of several analytical techniques, including X-ray crystallography, infrared spectroscopy, gas chromatography, and mass spectrometry. Section VII goes further into organic chemistry than most general chemistry courses do, but we feel students will find the articles stimulating and understandable. The last section provides myriad examples of chemistry in life. These include hydrogen bonding, optical rotation, chemical synthesis, molecular structure, weak acids and bases, oxidation-reduction, amino acids, proteins, carbohydrates, and nucleic acids. In addition to learning about protein structure and function, and the genetic code, students can learn about centrifugation, sequencing methods, molecular evolution, mutation, and what has become the central dogma of biology. The section is divided into two parts. The first, articles 28 through 31, deals with proteins. The second, articles 32 through 36, encompasses a discussion of nucleic acids.

Every article has been selected for its clarity and applicability to the material generally considered in a general chemistry course.

Have we gone too far into biology? We think not. Biological systems have been closely associated with chemistry for at least a century. Remember that organic chemistry originated in studies of the chemistry of biological extracts. The ultimate place for molecular biology in the undergraduate curriculum may be uncertain, but it is now biologists and chemists who must be reminded that what is molecular is chemical. They must also be reminded that without the tools of chemistry—X-ray crystallography, chromatography, ultracentrifugation, optical spectroscopy, isotope labelling and, lately, nuclear magnetic resonance—knowledge of molecular biology would not exist. Why not, then, use these most exciting applications of the techniques of chemistry to assist in the teaching of chemistry?

Are examples from molecular biology too complex to be clear to beginning students? Again, we think not. These examples do, moreover, provide students with an opportunity for establishing a relationship between scientific thought, their own thoughts about self-worth, and their attitudes toward life. The central dogma of molecular biology is as provocative, therefore, as Darwinism. It is good education.

We are pleased to acknowledge the contribution Linus Pauling has made to our book. His article written in 1950 provides an initial overview of the then-current state of chemistry and gives his predictions about the future successes to be expected in chemistry. In an epilogue beginning on page 419, written for this book, he reviews those earlier comments and provides several predictions about what the future promises beyond 1973. We express our appreciation to Professor Pauling for the model he provided us as an outstanding teacher and for the insights he has shared with us and our readers in his epilogue.

October 1973

James B. Ifft
John E. Hearst

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I

CHEMISTRY: A PERSPECTIVE IN TIME

I

CHEMISTRY: A PERSPECTIVE IN TIME

INTRODUCTION

The chemical properties of matter have been studied for centuries, yet chemistry as we think of it today is a young and fast-changing science. The first chemistry of the kind we consider important today began less than two centuries ago with the work of Lavoisier, which demonstrated the role of oxygen in combustion. The significant advances since then have all depended upon quantitative reasoning. In a way, Lavoisier and the chemists of his day were the beneficiaries of the first precise scientific instruments. But even for a century after Lavoisier, chemists' work consisted mainly of the analysis and synthesis of hundreds of small inorganic and organic molecules. It is doubtful if any of the nineteenth-century chemists could have even conceived that by the 1970's some major contributions of chemists would be the development of the transistor, plastics, and wonder drugs; that chemists would be creating a crisis with chemical pesticides and then devising new and safer ones; or that they would be dealing with environmental issues of energy production, birth control, and food production, or leading the investigations that have resulted in a detailed understanding of the structures of giant biopolymers and how these function.

Every science is dominated by a few great men and women who have made significant contributions to that science, given perspective to the efforts to extend its capabilities, and written with clarity and insight into the nature of their discipline.

Two such men, Linus Pauling and George Wald, have written the first two articles in this reader. Two decades ago each independently stepped back from his experimental work long enough to survey the status of his field. Both provide an excellent historical perspective and give an overview of the content of their disciplines as they seemed in 1950 (Pauling) and 1954 (Wald). Articles by these two scientists have been chosen not only because of the brilliance of their work and the breadth of their understanding of their disciplines, but also because they represent, between them, the full range of the field of chemistry as we view it today. Pauling's early contributions were primarily in the field of quantum mechanics. His early work on the nature of the chemical bond provided the foundation for much of our understanding of the properties of matter. More recently he has made significant contributions to biology, George Wald's discipline. Wald has elucidated the molecular mechanism of vision and has written extensively in the field of biochemistry.

Each man suggested, in the articles now reprinted in this reader, areas in which rapid progress might be made in the future. Because we are now a part of that future, it is exciting to look back at the perspective of these leading scientists.

In "Chemistry," Linus Pauling briefly traces the origin of chemistry from the pioneering work of Lavoisier up to the middle of the twentieth century. A comparison of the material described in this 1950 article with some of the content of the articles elsewhere in the reader is of interest. For example, a comparison of the periodic table used by Pauling in his article with that used by Frieden in "The Chemical Elements of Life," the fourth article, indicates that one of the ele-

ments, argon, had acquired a new symbol, Ar, rather than A, and that five additional elements had been discovered. Pauling mentions the importance of catalysts in the chemical laboratory and in the chemical industry. The articles by Faller, Haensel and Burwell, and Phillips, numbers 15, 16, and 31, indicate that not only has much progress been made in understanding the mechanism of catalysis by simple metallic surfaces, but that the mechanism by which the most intricate of all catalysts, enzymes, function has been determined for one enzyme—lysozyme. Pauling points out that the bases of thermodynamics were essentially complete early in this century. The articles by Hubbert and Summers, numbers 13 and 14, demonstrate a new thrust for thermodynamics in particular and science in general—the application of scientific knowledge to the solution of critical environmental problems, specifically, our energy resources.

In 1950, a large number of polymers of considerable practical use had been synthesized and an understanding of the structures of simple biopolymers was at hand. Article 29, by Merrifield, demonstrates that today chemists can synthesize not only Bakelite but one of the most complex polymers on Earth as well, a protein. We now understand not only the structure of methane but also the geometry of the genetic material, DNA. Our understanding of the electronic structure of molecules has deepened appreciably with the advent of high-speed computers, which have permitted accurate calculations of larger molecules. The elegant and informative diagrams in Wahl's article, 5, testify to the power of these new methods. In his article Pauling mentions the development of new analytical methods such as chromatography. Section VI, on instrumental methods of analysis, provides a number of elegant examples of how several analytical techniques—X-ray crystallography, infrared spectroscopy, gas chromatography, and mass spectrometry—have been developed or extended to yield the most detailed information available on molecular structure.

Pauling made a number of predictions in 1950 about where chemistry might be in the year 2000. We are now halfway through this time span. It is interesting, therefore, to see how far along we are in achieving the goals Pauling hoped would be met.

The first prediction was that we would be able to determine the rate of any chemical reaction from a fundamental understanding of the forces between atoms. In general, this goal has not been met yet. Although Phillips's article, number 31, indicates that at least for one enzyme, we do have a detailed understanding of how this particular catalyst, lysozyme, acts to sever a covalent bond, this understanding has not permitted a calculation of the rate of catalysis. Studies currently in progress using molecular beams should soon provide the background information needed to make predictions of reaction rates possible for very simple systems. Nor is it possible at present to synthesize catalysts to order. Haensel and Burwell point out in article 16 that there are innumerable reactions for which no catalysts are available.

Pauling predicted that a large number of inorganic polymers would be synthesized during this half century. The development of large polyphosphate molecules with interesting properties indicates that this is being done.

The prediction that the structure of proteins and nucleic acids would be determined has also been realized. It is reasonable to assume that the structure of genes will be known before the next quarter-century passes.

These are a truly remarkable set of predictions by a truly remarkable scientist.

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George Wald wrote "The Origin of Life" in 1954, just four years after Pauling wrote his article. A biologist at Harvard, Wald has been attracted by the chemical aspects of biology, and devoted much of his effort toward elucidating the molecular mechanism of vision. The versatility required for the solution of such a complex problem is illustrated by Wald's outstanding work, some of which is described in article 9, "Molecular Isomers in Vision," by Hubbard and Kropf. Wald's studies required knowledge of molecular spectroscopy and molecular structure as well as the physiology of the eye. Thus Wald has worked where chemistry and biology join, and his ideas and interests are representative of this interface.

In his article of twenty years ago, Wald was most interested in the chemical evolution of the organic molecules from which life is structured. At the time, the primary structures of carbohydrates, fats, proteins, and nucleic acids were known. No sequence information and no forms of secondary structures are mentioned in Wald's article, but the alpha helix was a recent discovery (see article 28, "Proteins," by P. Doty), and the sequences of the two chains of insulin had just been determined by Sanger and his co-workers (see "The Insulin Molecule" by E. O. P. Thompson, *Scientific American* Offprint 42). Wald's perspective was wider: how had the elementary molecules of life come into being?

The Russian biochemist A. I. Oparin published *The Origin of Life* in 1936; it was among the first references about a period of chemical evolution in the Earth's history. Nearer to the time of Wald's article, the first laboratory demonstration of the feasibility of the spontaneous creation of the organic molecules of life was made by S. L. Miller, who showed that a mixture of water vapor (H_2O), methane (CH_4), ammonia (NH_3), and hydrogen (H_2), when circulated past an electric spark, resulted in the formation of glycine and alanine, two amino acids. Now nearly all the amino acids have been formed, through minor modifications of this experiment, from the chemicals believed present in the early atmosphere of the Earth (see article 23, by Eglinton and Calvin, "Chemical Fossils," for other current investigations of chemical evolution).

Wald discusses the probability of unlikely events in relation to the formation of organic molecules and provides the reader with an elegant introduction to the basis of the second law of thermodynamics (which is an important topic in article 12; see "Ice," by L. K. Runnels). Wald argues that with sufficient time unlikely events can become probable, and that processes such as chemical evolution will occur. He discusses the competition between the forces that aggregate molecules into larger structures and forces of disruption, alluding to the constant motion of molecules and therefore the dynamics of evolutionary processes (see article 10, by B. J. Alder and T. E. Wainwright, "Molecular Motions").

Wald notes that structure is as important as composition, and that knowledge of three-dimensional structure can provide insights into the origin of life; it is interesting to see how other authors in this book have explored these ideas (see article 30, by R. E. Dickerson, "The Structure and History of an Ancient Protein," and article 31, by D. C. Phillips, "The Three-dimensional Structure of an Enzyme Molecule"). Wald uses collagen fibrils as an example of how structures can result from the forces of "integration" or spontaneous aggregation (see article 28, by P. Doty, "Proteins," in which the structure of collagen is discussed). He also alludes to hydrophobic interactions in a discussion of the aggregation of lecithins and cephalins into myelin figures (such interactions are described more fully in article 8, by

C. F. Fox, "The Structure of Cell Membranes").

The last part of Wald's article contains a remarkable discussion of the energy requirements of life. Wald is convinced that life originated as a fermentation process that used the energy stored in the organic molecules formed by chemical evolution. Before the depletion of these organic molecules, photosynthesis evolved, and cells became independent of the stored organic molecules for their energy. Instead, they synthesized their own organic molecules by using the energy of the sun's light and carbon dioxide, CO_2, in the atmosphere. Photosynthesis produced molecular oxygen, O_2, in the atmosphere, and finally respiration evolved as a far more efficient process for the production of energy (see article 19, by P. Cloud and A. Gibor, "The Oxygen Cycle").

The molecular mechanism of energy production and transfer in the living cell remains one of the exciting topics of study in contemporary chemistry (as Cloud and Gibor show in "The Oxygen Cycle" and as R. E. Dickerson shows in "The Structure and History of an Ancient Protein," article 30). The mechanism of vision is being studied extensively. The cell membrane has become the focus of much of the present interest in neurobiology (see article 8, by C. F. Fox, "The Structure of Cell Membranes").

And so, like Linus Pauling, George Wald was able, twenty years ago, to give a perspective of science that was remarkably accurate in predicting present interests.

1

CHEMISTRY

LINUS PAULING

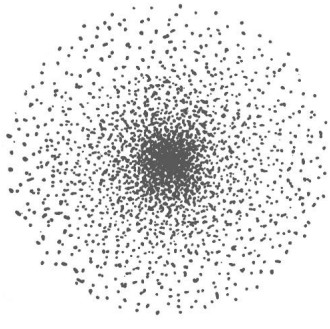
September 1950

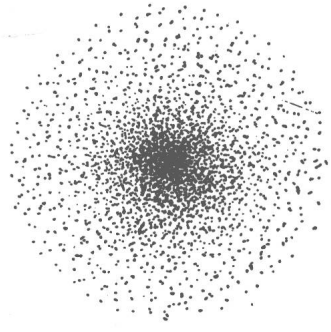
Aided by the new ideas of physics, the chemists have welded a huge body of facts into a unified system. Many of their fundamental advances have quickly become part of technology

The half-century we are just completing has seen the evolution of chemistry from a vast but largely formless body of empirical knowledge into a coordinated science. This transformation resulted mainly from the development of atomic physics. After the discovery of the electron and of the atomic nucleus, physicists made rapid progress in obtaining a detailed understanding of the electronic structure of atoms and simple molecules, culminating in the discovery of quantum mechanics. The new ideas about electrons and atomic nuclei were soon introduced into chemistry, leading to the formulation of a powerful structural theory which has welded most of the great mass of chemical facts into a unified system. At the same time great steps forward have been taken through the application of new physical techniques to chemical problems, and also through the continued effective use of the techniques of chemistry itself.

Chemistry is a young science. The chemical revolution took place only a little more than 150 years ago, when Antoine Laurent Lavoisier first clearly explained the role of oxygen in combustion and the nature of elementary and compound substances. Before Lavoisier chemical operations had been carried out according to recipes, and chemical reactions had been discovered only by haphazard trial. His new approach led to the rapid collection of a great amount of information about inorganic and organic substances. In 1828 Friedrich Wöhler achieved the first synthesis of an organic substance of animal origin (urea) from inorganic materials, and in the following decades many thousands of new substances were synthesized and their properties investigated. In 1852 Sir Edward Frankland formulated the theory of valence, and in 1858 Friedrich August Kekulé perceived that carbon has four valences; this insight gave great impetus to organic chemistry. Louis Pasteur's discovery of optical activity (the property, possessed by tartaric acid and many other substances, of rotating the plane of polarization of polarized light) and its explanation by means of the theory of the tetrahedral carbon atom by Jacob van't Hoff and Joseph LeBel effectively completed the classical structural theory of organic chemistry. Guided by this theory, and making use of many special techniques of analysis and synthesis, the organic chemist then investigated great numbers of natural substances and new substances made in the laboratory. Many of them were found to be valuable as dyes, as medicines, in foods and for special industrial purposes, and an immense organic chemical industry was developed, largely based on coal tar.

DURING the first half of the 20th century organic chemistry has advanced along an extension of this road. The theory of the structure of organic molecules has become more precise and more useful through the incorporation in it of the theory of resonance and the





ATOMS AND MOLECULE illustrate the covalent chemical bond. At the left are two hydrogen atoms, each with an electron represented by the time average of its motion about the nucleus. At the right is the hydrogen molecule, in which two nuclei share two electrons. The drawings in this article are by Roger Hayward and are from Pauling's books *General Chemistry* and *College Chemistry*, published by W. H. Freeman and Company.

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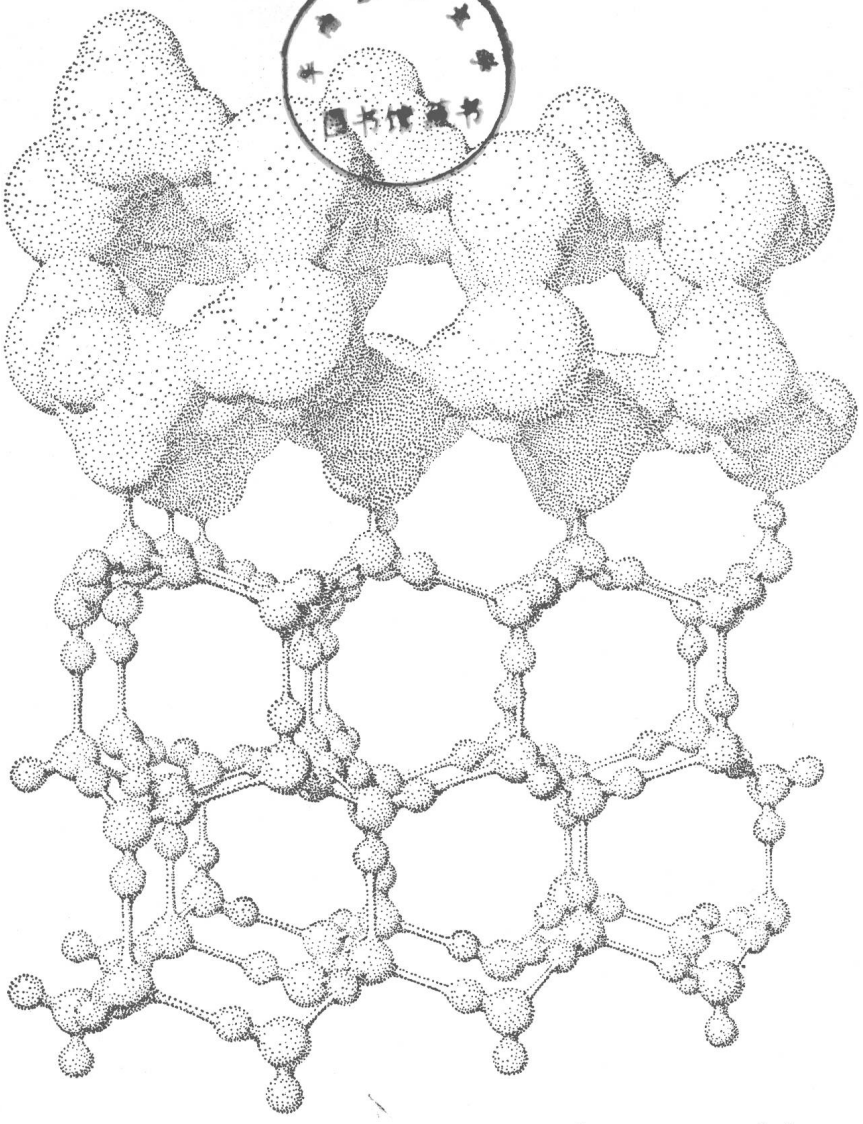
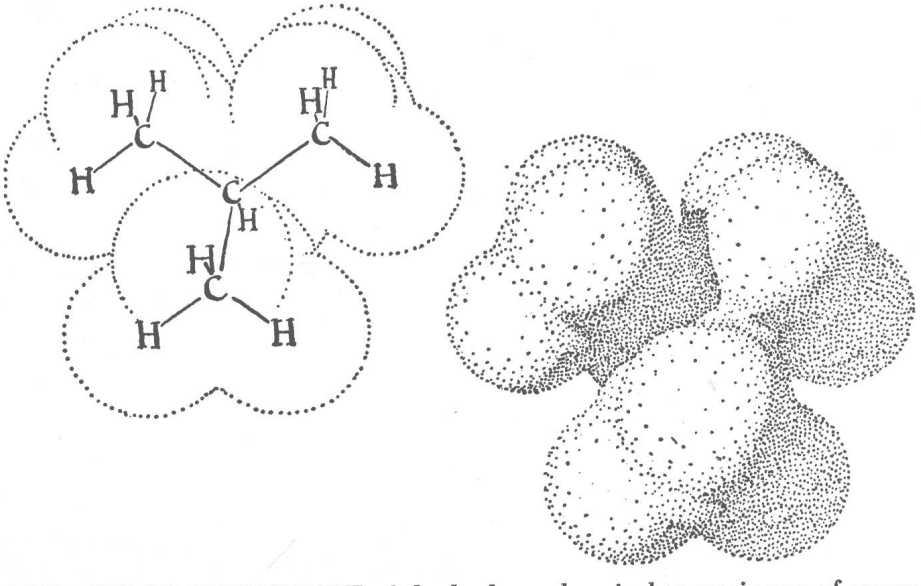
electronic theory of valence in general, and also of information about distances between atoms, bond angles and other features of molecular structure determined by spectroscopic analysis or by the diffraction of X-rays or electron waves. Many new synthetic procedures and analytical methods have been discovered. One of the most valuable new methods is the chromatographic technique for separating pure constituents from mixtures of substances, which was invented by Michael Tswett in 1906. In industrial chemistry we have seen an important shift: petroleum has to a great extent replaced coal tar as the raw material for the preparation of organic compounds.

Another striking aspect of organic chemistry in our century is the part played by special catalysts, both in the laboratory and in the industrial plant. This 20th-century development, which had its first success in the production of catalysts for the conversion of atmospheric nitrogen into ammonia and nitric acid, has risen to immense importance, especially in the manufacture of valuable products from petroleum. Great progress has resulted also from the expansion of the field of effective endeavor of the organic chemist to include giant molecules – molecules containing thousands or millions of atoms. In the 19th century the organic chemist could work confidently and effectively only with relatively simple substances. Then during the first decades of the 20th century he made effective headway in analyzing the structure and properties of macromolecular natural materials such as cotton, rubber and wood. Armed with knowledge obtained in this way, he essayed to synthesize new fibers, new elastomers, new plastics, and he succeeded not only in obtaining satisfactory substitutes for many natural materials but also in making many materials with far superior properties.

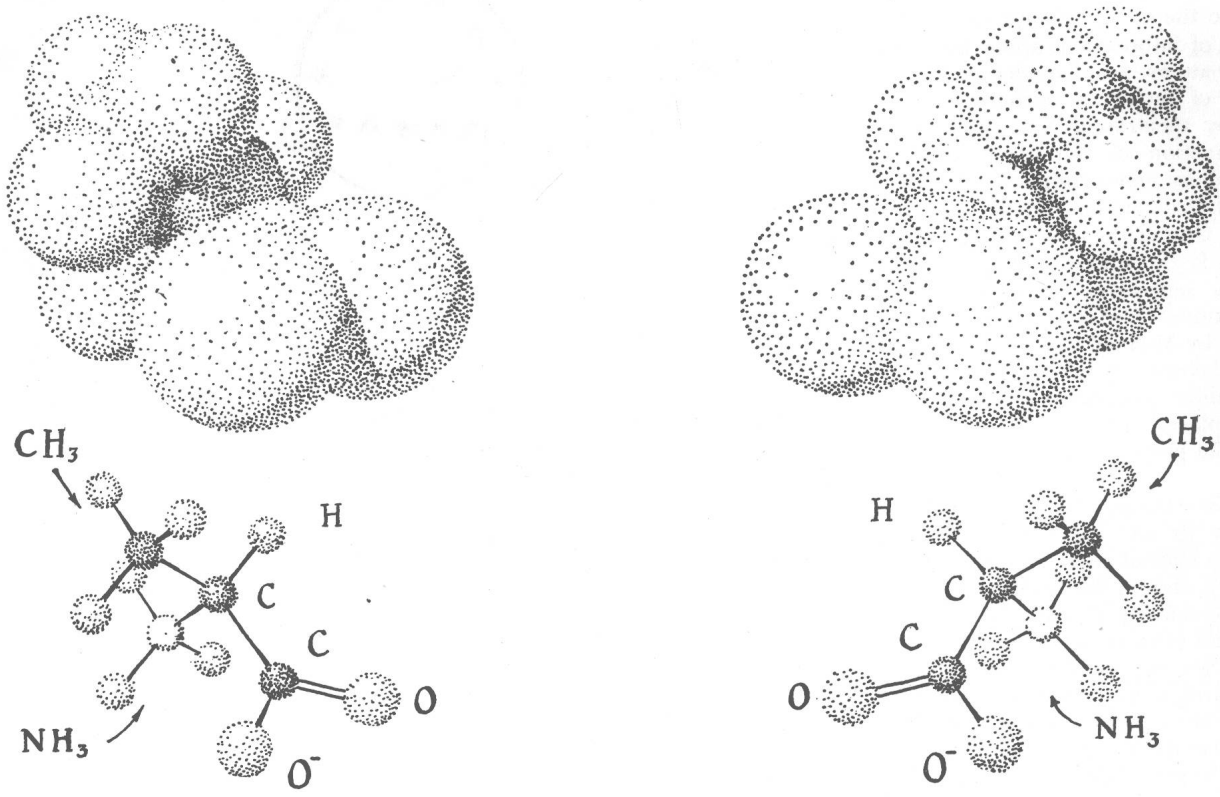
In inorganic chemistry there was a period of inactivity in the first part of our half-century, and then came a rebirth. The last two decades have seen the completion of the periodic table as far as atomic number 98, with the addition of technetium (43), promethium (61), astatine (85), francium (87), neptunium (93), plutonium (94), americium (95), curium (96), berkelium (97) and californium (98). Spectroscopic and diffraction studies of the structure of molecules and crystals have provided a penetrating insight into the nature of the interactions between atoms and molecules. This has been combined with quantum mechanics to yield a broad and powerful electronic theory of valence and chemical combination, permitting the correlation of the structure and properties of inorganic substances as well as of organic substances. The theory of resonance of molecules



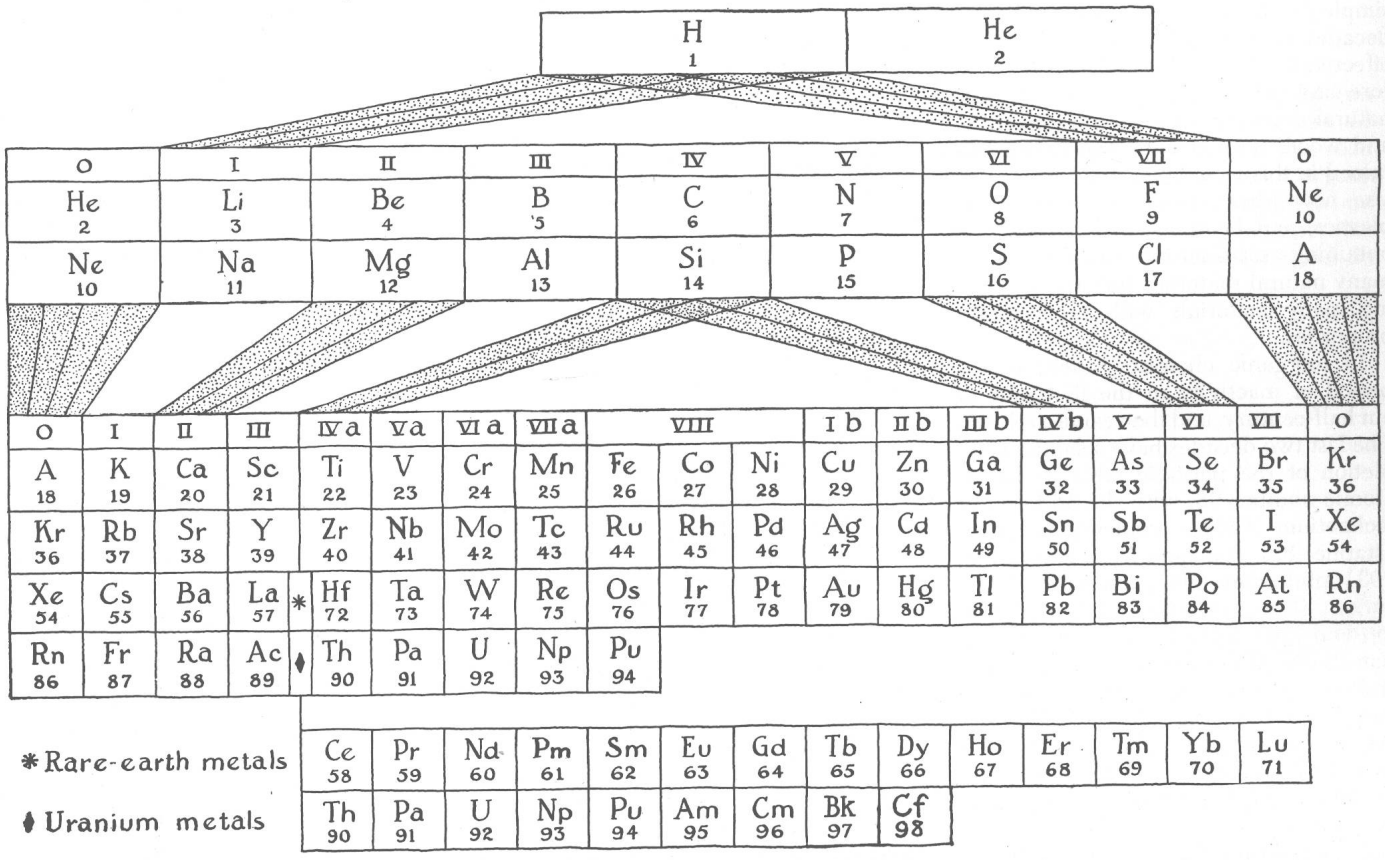
CRYSTAL STRUCTURE of ice is based upon the geometry of the water molecule. The molecules at the top of this drawing are shown with their atoms and interatomic distances in the correct proportion. The atoms at the bottom have been reduced in size to clarify the structure of the crystal.



MOLECULAR STRUCTURE of the hydrocarbon isobutane is one of many of such structures worked out by organic chemists. At the right the atoms and the interatomic distances of the molecule are shown in their correct proportions. At the left is a diagram showing the skeletal geometry of the molecule.



THE AMINO ACID alanine is one of the 20-odd amino acids that make up proteins. Like all the other amino acids except one, alanine has two stereoisomers or molecular mirror images: *d*-alanine (*left*) and *l*-alanine (*right*). Curiously only amino acids of the *l* configuration are found in proteins. Although the structure of the amino acids is well known, their arrangement in proteins is one of the fundamental problems of chemistry.



THE PERIODIC TABLE of the chemical elements has in recent years been filled in and enlarged. Four elements have been inserted into the former table: technetium (Tc), promethium (Pm), astatine (At) and francium (Fr). The table has also been extended beyond uranium (U) by neptunium (Np), plutonium (Pu), americium (Am), curium (Cm), berkelium (Bk) and californium (Cf). Atomic number of each element is beneath symbol.

among two or more valence-bond structures has found valuable applications in both inorganic and organic chemistry.

IN RECENT years practical inorganic chemistry has developed rapidly. Many new and important compounds of fluorine and silicon (fluorocarbons, silicones) have been made. The manufacture of plutonium and the controlled release of atomic energy have been accompanied by extensive chemical studies of uranium and the transuranium elements, of the rare-earth metals and of the elements formed as fission products.

Chemical thermodynamics—the study of the chemical effects of energy and temperature — is essentially a 20th-century development. It is true that the first and second laws of thermodynamics, dealing with heat transfer and entropy, had been formulated by 1851, and that Josiah Willard Gibbs had published his masterful series of papers on the application of thermodynamics to chemical phenomena in the period between 1873 and 1878. But the impact of this work on chemistry was not felt until after 1900. At the turn of the century Walter Nernst discovered the third law of thermodynamics, relating to the behavior of substances at low temperatures, and many chemists, among whom Gilbert Newton Lewis deserves special mention, labored to collect thermodynamic data and to weld them into a practical system. Quantum statistical mechanics has shown how the knowledge of interatomic distances and force constants obtained from spectroscopic and diffraction studies can be used in the application of chemical thermodynamics to practical problems. In the design of industrial plants the modern chemist — especially the petroleum chemist—may depend on thermodynamic information obtained by calculation from interatomic distances in molecules.

Information about the thermodynamic properties of substances, especially the absolute entropy, for application of the third law, often is obtainable only by measurements made down to very low temperatures. Early in the present century Kamerlingh Onnes, extending the pioneer work of Sir James Dewar, obtained temperatures slightly below 1 degree Kelvin by the evaporation of liquid helium. For some time it seemed impossible to achieve a closer approach to absolute zero; then William F. Giauque suggested in 1924 and later put into practice a new method—cooling by demagnetization. With this technique he and other investigators succeeded in reaching temperatures as low as about .001 degree K.

Thus chemical thermodynamics has rapidly developed to the point where it is possible for tables of the thermodynamic functions of chemical substances to be constructed. With the aid of these tables a reliable prediction can be made as to whether any chemical reaction involving these substances can be made to take place or is thermodynamically impossible. This prediction, however, does not satisfy the chemist; he wants also to know whether the reaction will proceed rapidly enough to provide a satisfactory yield of the product in the available time. The study of the speed of chemical reactions is another important branch of physical chemistry. In this field some progress has been made, but the goal of the formulation of a complete theory of reaction kinetics, analogous to the now essentially completed system of chemical thermodynamics, seems to lie far ahead.

WHAT will the next 50 years bring? How much greater understanding and mastery of chemical substances than we now possess will the chemist of the year 2000 have? We may hope that he will have obtained such penetrating

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knowledge of the forces between atoms and molecules that he will be able to predict the rate of any chemical reaction with reasonable reliability. In order to do this he will have to find out how catalysts work in accelerating chemical reactions. At the present time no one knows why a particular catalyst is effective for a particular reaction; the preparation of catalysts is essentially an empirical art. Perhaps in the next half-century chemists will succeed in preparing catalysts to order. In addition the chemist of the future may well be able to make use of new aids to cause desired chemical reactions to take place. One of these aids might be high-energy rays—alpha particles, electrons, positrons, gamma rays —made available by the uranium pile. As new materials capable of withstanding very high temperatures and pressures are developed, new chemical reactions can be made to occur. And the development of a greater understanding of the relation between the molecular structure and the chemical and physical properties of substances should permit predictions to be made as to the types of new substances that need to be synthesized for various special purposes.

The recent successful development of valuable new compounds of silicon and fluorine suggests that other elements too may be put to additional uses. The chemistry of very large inorganic molecules has been neglected. We may look forward particularly to progress in the study and use of compounds of elements that have a strong tendency to be present in large molecules, notably phosphorus, vanadium, molybdenum, wolfram and tantalum.

The metals constitute a great class of substances that deserves more thorough study by chemists. Organic and ordinary inorganic materials have been assiduously investigated year after year, but metals and alloys, including intermetallic compounds, have been neglected. The coming half-century should see the development of a sound theory of the structural chemistry of metallic substances. Metallography will thereby become a science, and the straightforward formulation of new alloys with special properties and valuable uses will become possible.

IN organic chemistry there exists a field with equally broad room for progress: investigation of the structure of physiologically active substances, especially vitamins and drugs, and the synthesis of new ones. This work has been handicapped by the lack of a theory of the molecular structural basis of physiological activity. The next half-century should witness the development of such a theory. This would involve also the solution of the problem of the structure of proteins, nucleic acids and other macromolecular constituents of living organisms, including enzymes and ultimately genes. When the mechanism of drug action has been elucidated, it will be possible for chemists to make greater and greater contributions to the problem of good health and the control of physical and mental disease. Instead of synthesizing great numbers of substances at random, the chemist will be able to plot the molecular structure of the most likely substance for each use and synthesize it for trial.

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