Chemical Dynamics: A Current Review (1966)

Pages
80

Size
7 x 10

ISBN
0309364205

Panel on Chemical Dynamics; Committee for the Survey of Chemistry; Division of Chemistry and Chemical Technology; National Research Council

Chemical Dynamics
A Current Review

Report of the Panel on Chemical Dynamics
of the Committee for the Survey of Chemistry
Division of Chemistry and Chemical Technology
National Academy of Sciences National Research Council

Publication 1292-B
NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL
WASHINGTON, D. C. 1966

PANEL ON CHEMICAL DYNAMICS

George S. Hammond, California Institute of Technology, Chairman
Myron L. Bender, Northwestern University
Michel Boudart, Stanford University
Robert E. Connick, University of California at Berkeley
Aron Kuppermann, California Institute of Technology
Herbert A. Laitinen, University of Illinois
B. S. Rabinovitch, University of Washington

COMMITTEE FOR THE SURVEY OF CHEMISTRY

Frank H. Westheimer, Harvard University, Chairman
William O. Baker, Bell Telephone Laboratories, Inc.
Theodore L. Cairns, E. I. du Pont de Nemours & Company
Melvin Calvin, University of California at Berkeley
Bryce L. Crawford, Jr., University of Minnesota
Herbert S. Gutowsky, University of Illinois
Franklin A. Long, Cornell University
Robert W. Parry, University of Michigan
Kenneth S. Pitzer, Rice University
Charles C. Price, University of Pennsylvania
John D. Roberts, California Institute of Technology
Harrison Shull, Indiana University
Walter H. Stockmayer, Dartmouth College
Gilbert Stork, Columbia University
Henry Taube, Stanford University

Martin A. Paul, National Academy of Sciences—National Research Council, Special Consultant

Available from

Printing and Publishing Office
National Academy of Sciences
2101 Constitution Ave., N.W.
Washington, D. C. 20418
Price $3.00

The Committee on Science and Public Policy of the National Academy of Sciences has appointed committees to survey several of the basic sciences. In the course of preparing its report, Chemistry: Opportunities and Needs (NAS-NRC Publication 1292, November 1965), the Committee for the Survey of Chemistry appointed panels of distinguished scientists to prepare reports on specific areas of chemistry. These panel reports, of widely varying scope, provided much of the information and expert opinion that constitute the Survey.

Many of the panel reports necessarily contained more valuable information and more detailed discussion than we could adequately summarize in the space at our disposal. We therefore present here the panel report on Chemical Dynamics in its entirety. The Committee for the Survey of Chemistry does not necessarily agree with or endorse all the opinions or conclusions presented; they are of course those of the authors. We believe, however, that this report contains important subject matter, and that it will be interesting and informative to many readers. We wish to thank the panel members and especially the chairman, Dr. George S. Hammond, for their contribution to chemistry. We wish also to acknowledge a grant from the American Chemical Society and additional support from the National Science Foundation that enabled this study to be undertaken.

Frank H. Westheimer, Chairman
Committee for the Survey of Chemistry

CONTENTS

I

INTRODUCTION

Chemical dynamics is the study of matter in the process of chemical change. The dynamicist asks, "How do reactions occur? What forces drive them? Why are they so fast, or so slow?" The two aims in the study of chemical dynamics are to understand interactions of matter with matter, and to control some chemical changes and anticipate the inevitability of others.

The two sets of principles that underlie chemical change are energetic relationships and kinetic considerations. Although the latter is specifically the field of chemical dynamics, we must discuss energy relationships briefly since they define the framework within which dynamics can operate. The chemical potential (potential capacity for undergoing chemical change) defines the state of chemical systems at equilibrium. Understanding chemical potential is a problem in structural chemistry since a full description of the molecular structure of any system should include complete analysis of the energy relationships. In practice, much of our knowledge concerning energetic relationships still depends upon experimental measurement of the chemical composition of systems that have been brought to equilibrium. However, no description of the energy relationships in equilibrated systems can of itself be sufficient for understanding and controlling chemistry. One must also deal with the rates at which the equilibrium condition is established. The rates of chemical changes vary almost without limit, having characteristic times ranging from less than a trillionth of a second to eons. Not only do different reactions proceed at widely varying rates but the rate of a given reaction may be varied through many orders of magnitude by changes in conditions such as temperature, the reaction medium, or the nature of catalysts.

Research in chemical dynamics may take many forms. In complex systems, such as living organisms, effort may be focused on simple definition of the sequence of changes that are components of an over-all process. In another case, emphasis may be placed upon variations in rates consequent to changes in the environment or in the structures of reactants. The work may be designed to remove the mystery that still surrounds the remarkable effects of catalysts, or the program may involve observation of the interactions between pairs of atoms or molecules of dilute gases. Finally, there is an active field of purely theoretical study in which models of reacting systems are chosen and subjected to mathematical analysis according to methods of both classical and quantum mechanics. A great deal of experimental work is directed toward testing the results of theoretical analysis. Although all theory of reaction rates is manifestly incomplete, and must remain so for the forseeable future, there is probably no field of science in which theoretical study has been as rapidly and fruitfully extrapolated to the complex as in chemical dynamics.

There is considerable interaction between dynamics and other areas of chemistry. Developments in structural chemistry provide concepts and language that are indispensable to the discussion of dynamic problems. Feedback in the other direction also occurs. Study of the kinetics of reactions has often pointed to the existence of transient intermediates that turn out to be new and important structural types. Chemical dynamics is fundamental to the development of synthetic chemistry and, conversely, clever synthetic work is often required to prepare the right compounds for testing theories of dynamics.

Most chemical processes are actually complex networks of steps called elementary processes. A suitable definition of an elementary process is an indivisible unit of chemical change. Since the definition is purely operational, a change may be called an elementary step in one investigation even though it is treated as complex in another. For example, shortening of the time scale of observation or changing the sensitivity of some method of detection may change the count of discrete steps in an over-all chemical process. Most reacting chemical systems are like large intricate machines in which the component parts are elementary reactions. Our real hope for controlling chemical reactions lies in understanding elementary steps and the cooperation and competition among them. It is almost inevitable that as complex reaction networks are unraveled and the elementary steps are identified and understood, over-all chemical processes will become increasingly subject to precision control. Eventually all large-scale chemical manufacturing may be controlled by computers fed with quantitative instructions couched in the language of chemical dynamics.

Many of the recent advances in chemical dynamics would have been inconceivable without the new tools that have become available within the last two decades. Questions that would have been unthinkable 20 years ago can now properly be asked and answered experimentally; studies that would once have required months or years can now be completed more satisfactorily in days or weeks.

An abundance of tools is needed for the study of reactions under usual conditions because the problems are really enormously complex. Each individual molecule generally contains too many fundamental particles (electrons and nuclei) to solve the quantum-mechanical equations that describe it. Furthermore, any ordinary chemical system contains billions of billions of molecules. Even an unreactive system, at ordinary temperatures, is in a constant state of flux since the thermal energy of the system flows continuously between molecules and from spot to spot within molecules. The total description of an unreactive system presents staggering difficulties, and an entirely rigorous description of of a system undergoing chemical reaction is virtually inconceivable since the lifetimes of molecules in the act of consummating a chemical transformation are extremely short.

Despite the complexity of its problems, chemical dynamics has developed remarkably during the past few decades. At the turn of the century many chemical reactions were known, but useful information concerning them was almost entirely empirical and encyclopedic. At the present time the mechanisms (that is, the elementary steps in a complex network) of many reactions are known in considerable detail. Furthermore, knowledge gained in the study of one reaction can now ordinarily be systematically extended to give rather precise predictions concerning other reactions. The theory of chain reactions was entirely worked out by chemical dynamicists long before physicists used nuclear chain processes in making the first atom bombs. Many useful chain reactions can be turned on or off at the will of the chemist. Good examples are the polymerization reactions used in production of synthetic elastomers (rubber) and many common plastics.

Development of the theory of reaction rates moved rapidly in the 1920's and 1930's and then slowed down. Now, theory is again surging ahead, partly because of the availability of new techniques for studying elementary processes under controlled conditions, partly because of the advent of high-speed computers, and partly because new ideas continue to occur to men in the field. An impressive number of the new tools of chemistry has been developed by chemical dynamicists. Among these are a number of ingenious devices for monitoring the rates of fast reactions, pulsed excitation methods in which large amounts of energy are pumped into a system during a microsecond or less, and a host of versatile new electrochemical techniques.

Auspicious beginnings have been made in understanding the dynamics of biochemical processes. Many of the pathways of carbon compounds in metabolism are now well known and systematic attacks are being made on the detailed kinetic analyses of such complex natural processes as photosynthesis and the enzyme-catalyzed splitting of proteins.

We believe that the United States leads the world in chemical dynamics although fine work in the field is being done in many European countries. At the present time, Henry Eyring, Paul Bartlett, Henry Taube, Saul Winstein, Dudley Herschbach, and a number of other Americans are unchallenged leaders in their respective areas of chemical dynamics. The most advanced theoretical work is now done in this country as well as the best work in the field of solution and gas-phase kinetics. In studies of fast reactions and detection of chemical transients, Manfred Eigen in Germany and George Porter in England have clearly set the pace for the world community, although American contributions in both fields are substantial. It is significant that areas in which men from other countries have established leadership are those in which large investment is needed for construction of new instruments. On the other hand, this country has clear leadership in the field of radiation chemistry, which depends heavily on the availability of expensive nuclear reactors which, however, were built primarily for other purposes.

That a field as complex and important as chemical dynamics must have a brilliant future seems quite obvious. Moreover, a prediction that the field will develop rapidly in the immediate future is not unrealistic. Work with molecular beams has just started to yield truly significant results and new machines are now being built that will be even more efficient.

Major obstacles to doing new and important theoretical calculations have disappeared. Detailed chemical description of the active sites in several enzymes seems imminent and equal success with others will follow. Precision description of detailed mechanisms, which has been limited largely to a relatively small number of organic reactions, is starting to spread into new areas. A realistic list of fruitful developments in the near future could include dozens of such items.

One measure of the vitality of any field is the number of bright young men entering it. Reliable statistics on this count are difficult to gather but an example may help. At an international symposium on organic photochemistry held in Strasbourg in the summer of 1964 at least 100 of the 150 registrants were under 35 years of age. In short, the manpower, the methods, the ideas, and the enthusiasm are all available to move chemical dynamics at an unprecedented pace during the next few years.

II

THEORY AND EXPERIMENTAL STUDY OF ELEMENTARY REACTIONS

GENERAL CONSIDERATIONS

Most chemical changes occurring in nature or in industrial processes are complex. That is, they can be resolved into two or more elementary steps. Understanding of the over-all process requires separation and direct study of two problems: identification of the elementary steps, and characterization of the factors that control the rates of these simplest definable steps.

Let us illustrate these two points with a relatively simple reaction—the pyrolysis of ethane. The reaction occurs at temperatures above 500°C and is a prototype for the complex changes involved in the pyrolytic cracking of petroleum.* Superficially the reaction appears simple; the principal products are ethylene and hydrogen. Small amounts of other products are also formed.

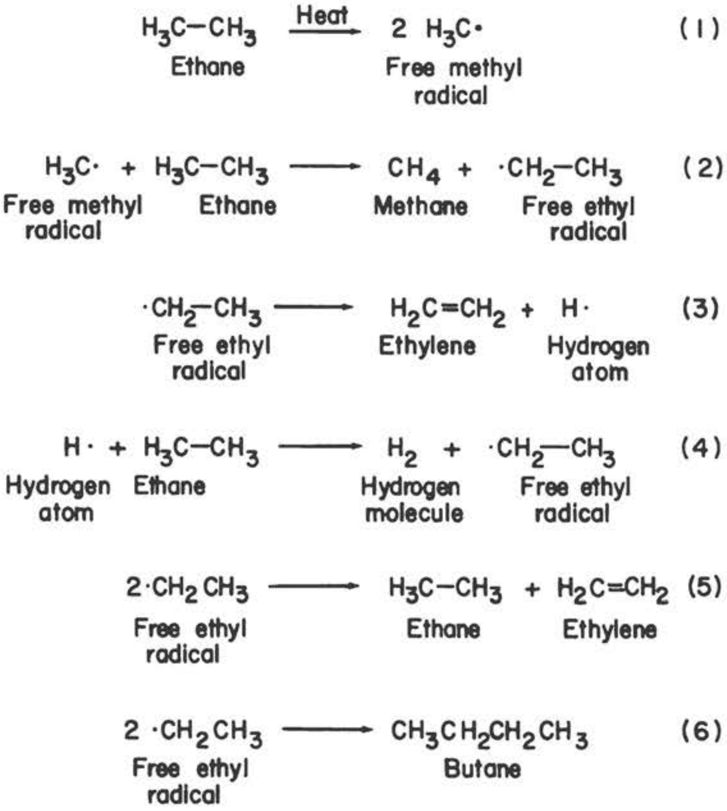
$$\underset{\text{Ethane}}{CH_3{-}CH_3} \longrightarrow \underset{\text{Ethylene}}{CH_2{=}CH_2} + H_2 + \text{other minor products}$$

Unsatisfactory attempts were made to account for the influence of various factors, such as the effects of trace additives on the reaction rate, using the assumption that the reaction is an elementary process

---

*Another method of cracking, involving the use of solid catalysts (Section III), is now frequently used in the petroleum industry. The detailed chemistry of the catalytic process is only partially understood and is the subject of continuing intense study.

resulting from the decomposition of single energetic molecules. Detailed study showed that the "simple" change is accomplished by the following network of elementary steps:



$$H_3C{-}CH_3 \xrightarrow{\text{Heat}} 2\ H_3C\cdot \qquad (1)$$

$$H_3C\cdot + H_3C{-}CH_3 \longrightarrow CH_4 + \cdot CH_2{-}CH_3 \qquad (2)$$

$$\cdot CH_2{-}CH_3 \longrightarrow H_2C{=}CH_2 + H\cdot \qquad (3)$$

$$H\cdot + H_3C{-}CH_3 \longrightarrow H_2 + \cdot CH_2{-}CH_3 \qquad (4)$$

$$2\cdot CH_2CH_3 \longrightarrow H_3C{-}CH_3 + H_2C{=}CH_2 \qquad (5)$$

$$2\ \cdot CH_2CH_3 \longrightarrow CH_3CH_2CH_2CH_3 \qquad (6)$$

This is a moderately complicated chain reaction. The over-all process is initiated by reaction (1) and terminated by reactions (5) and (6). Note that there is an interesting reciprocal relationship between reactions (3) and (4). Reaction (3) produces hydrogen atoms which are consumed in reaction (4) and the latter process furnishes free ethyl radicals for reaction (3). This pair of reactions can go through many cycles, producing many molecules of ethylene and hydrogen, for every initiation and termination act. Consequently, the over-all rate is much faster than the rate of reaction (1). The over-all rate is a complex function of the rates of the individual steps:

$$R_{(\text{overall})} = R_{(3)} \left(\frac{R_{(1)}}{R_{(5)} + R_{(6)}} \right)^{1/2}$$

Each of the steps has become reasonably well understood in recent years. Furthermore, the understanding is good enough to allow fairly accurate prediction of the effects on each of the rates if a more complex hydrocarbon is substituted for ethane. The mechanism includes both kinds of elementary processes known to chemical dynamics. Reactions (1) and (3) are unimolecular reactions and the others are bimolecular reactions. Much of the knowledge about elementary reactions can be summarized by discussion of these two basic reaction types.

One of the aims of chemical dynamics is to understand elementary reactions in intimate molecular detail. Before attempting to explain the meaning of intimate understanding, we shall discuss a few important characteristics of reaction rates. Some reactions are slow, requiring input of large amounts of energy; on the other hand, some bimolecular reactions may take place on every encounter of the reactants. Furthermore, there is no simple correlation between the over-all energy change in a reaction and the "activation energy" required to produce it. The necessity for supplying an activation energy to drive a reaction has been compared with the problem that people face in going over a mountain from one valley to another. The mountain is analogous to the potential barrier which must be passed before the reaction can completed. A molecular complex that has accumulated the necessary activation energy, and is organized so that it can pass into products, is known as an activated complex; it is analogous to a mountaineer who stands at the crest of a pass ready to start the downhill path into the next valley. It is reasonable that there should be an activation energy even in reactions that will ultimately produce energy; that is, where the products will be more stable than the reactants. Stabilization of the products can only be realized after the atoms have settled down to the stable, bonded arrangement characteristic of the undisturbed state. Considerable distortion of the reactants may have to precede formation of some of the new bonds in the products.

Just as important as accumulation of the energy required to pass the potential barrier is the requirement that the activation energy be available in the right form. Consider, for example, the decomposition of an ethane molecule to give two methyl radicals, shown in Reaction (1) above. To a first approximation, energy must be supplied to stretch and break the carbon-carbon bond. It can be surmised that molecular energy concentrated in vibrations of the carbon-hydrogen bonds will not necessarily contribute to breaking the carbon-carbon bond. Description of the intimate process of elementary reactions must include details of the transfer of energy between molecules and the flux of energy within molecules. Such descriptions can be formulated in terms of either classical mechanics or quantum mechanics. The former, although highly complex, are more manageable than quantum-mechanical methods. Consequently, assessment of the importance of quantum effects is a major problem in the theory of reaction rates. The hope that special quantum effects will be small is not just a reflection of laziness; neither classical nor quantum-mechanical treatments can be carried out with complete rigor, but a more detailed analysis can be made if the classical approximation is adequate.

A molecule may have several kinds of energy. It possesses kinetic energy associated with movement of the entire molecule through space; this is known as translational energy. In addition, the molecule may have various kinds of internal energy. First there is rotational energy of the molecule as a whole; this is analogous to the energy of a top spinning in one place. The molecule also has vibrational energy arising from oscillations of the atoms in relation to each other; a rough model for a vibrating molecule can be made by taking an ordinary molecular model made from balls (atoms) and sticks (bonds) and replacing the sticks with springs. Finally, the molecule has energy arising from the interaction of negative electrons and positive nuclei, known simply as electronic energy.

A large proportion of all chemical reactions involves molecules in their lowest electronic energy states. The internal energy required to allow a molecule to react is stored in vibrational and rotational motions. Description of the internal energy content of a molecule as a function of its internal geometry is called a potential (energy) surface. Fundamental understanding of reactions not involving electronic excitation* requires information from all possible sources concerning the nature of potential surfaces.

Energy may be supplied to molecules by, for example, collision with other molecules (thermal activation), absorption of light (photochemical activation), or preparing the molecule by an exothermic reaction (chemical activation). Let us examine the case of thermal activation. We seek answers to various questions. How long does a collision between two molecules last? How efficiently can translational energy be converted to internal vibrational and rotational energy during the collision? Does the efficiency of such energy conversion depend on the prior level of internal excitation? How does it depend on the angle of approach? How effectively can vibrational and rotational energy be transferred between molecules during collision? Such questions define the problem of intermolecular energy transfer.

Another series of questions can be posed concerning the detailed behavior of a molecule after it has been activated. How long does an energized molecule live before it flies apart? How fast does energy flow from one place to another within the molecule? Can rotational energy contribute to bond breaking? If the molecule contains more than the minimum energy required for a reaction, where does the excess energy appear in the products? These processes of intramolecular

---

*Reactions involving electronic excitation will be discussed in the section dealing with photochemistry and radiation chemistry, page 46.

energy transfer, occurring during collisions, compete with deactivation by intermolecular transfer.

A third series of questions pertains to the collective behavior of samples consisting of large numbers of molecules; that is, the statistical mechanics of the system. Answers to problems concerning the behavior of individual molecules or molecular pairs must be extended to provide rate laws governing reactions in macroscopic samples. One can imagine a liter vessel of gaseous ethane heated to 500°C with decomposition being prevented by an entirely fictitious agent, such as one of Maxwell's demons.* The molecules would distribute themselves in statistical equilibrium among the many available energy states of the system. If the demon were suddenly removed from the system, the equilibrium would be disturbed by decomposition of some of the highly energetic molecules in the system. If the rate of decomposition were slow compared with the rate of energy exchange among the components of the system, the law governing the reaction rate could be easily obtained from a simple model and would be

$$\text{Rate of reaction} = NAe^{-E^*/kT},$$

where

N = number of reactant molecules in the system,
A = the frequency of decomposition of molecules having energy contents equal to the critical activation energy,
E^* = critical activation energy,
k = a fundamental (Boltzmann) constant, and
T = absolute temperature.

The law really involves the assumption that activated complexes are in energetic equilibrium with the other states of the reacting system. The situation is rather like the hydrodynamic problem of the flow of liquids through nozzles under pressure. The liquid in the orifice is essentially in equilibrium with the fluid upstream but not with that on the low-pressure side. The assumption is attractive and the consequences simple, but we do not really know the limitations of the law. Furthermore, the frequency factor, A, has the properties of a "fudge" factor. We must ask how A varies with the temperature and how A is related to the structure of the molecule.

*In considering the second law of thermodynamics, Maxwell found it convenient to imagine the existence of a demon who could stand at a gateway separating two samples of a gas and discriminate among the molecules passing between the two chambers. Chemists have so coveted the abilities of the demon that they frequently call upon him or his peers to impose the artificial restraints necessary to maintain an unrealistic condition existing in a theoretical model.

The remainder of this section contains snapshots of current experimental and theoretical attempts to answer fundamental questions concerning elementary reactions. Examples of the resolution of complex chemical networks into component elementary reactions will be given in later sections. It is convenient to separate the discussions of unimolecular and bimolecular reactions.

UNIMOLECULAR REACTIONS

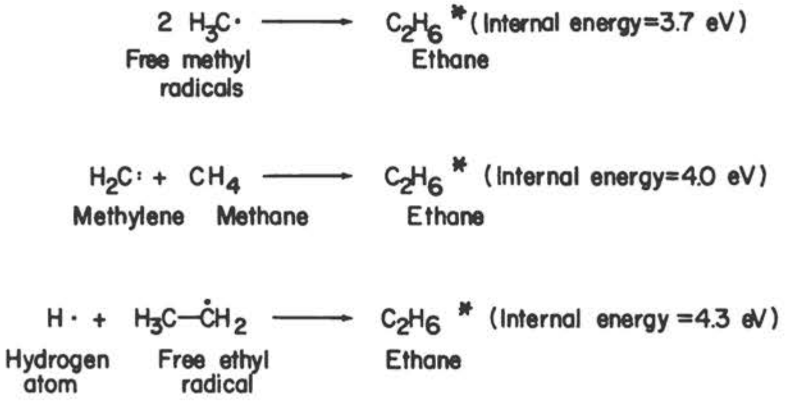
In a unimolecular reaction, a single molecule undergoes some chemical change after it has acquired the requisite activation energy. The energy required to pass over the potential barrier is put into the molecule by intermolecular energy transfer; organization of the energy so that it can be used to accomplish the reaction involves intramolecular energy transfer. Although the same two processes of energy transfer are also crucial in bimolecular reactions, they are most easily studied in connection with the simpler reaction type.

Intermolecular Energy Transfer

Energy is exchanged between two molecules when they collide. Transfer of translational energy is the most probable kind of exchange but is of trivial consequence. Before energy can cause a chemical change it must be converted to internal energy. The law of conservation of momentum prohibits the conversion of translational energy to vibrational or rotational energy in an isolated molecule. Consequently, the principal concern of chemical dynamics is with the conversion of translational energy to internal energy and the exchange of internal energy during collisions. Prior to 1950 nearly all work involved molecules at low levels of excitation. The most elegant experimental work was carried out by physicists who used the method of sound-dispersion to monitor changes in translational energy. Results were usually interpreted in terms of the classical theory of Landau and Teller, according to which energy is transferred mainly when the incident particle is moving swiftly and its interaction with the molecule lasts for many of the vibrations of the latter. The vibrating molecule was viewed as two atoms coupled by very strong springs. An important consequence of the quantum-mechanical version of the theory was that at most one quantum of vibrational energy could be transferred per collision. Experimental studies usually involved vibrational excitation of diatomic molecules in collision with monoatomic gases such as helium and krypton. Translational-vibrational energy interconversion was found to be a relatively improbable event, occurring only once in 10^6 - 10^9 collisions.

Some important variables were noted. The probability of energy conversion increased at higher temperatures, and light atoms such as helium were more effective than heavy atoms such as krypton in donating their translational energy to the molecules. The results were reasonably in accord with the Landau-Teller theory.

Despite the encouraging results, there was reason to believe that this attractively simple picture was not really pertinent to chemical reactions. The behavior of molecules at high levels of vibrational excitation, corresponding to the energy content of chemically reacting species, might be different. Moreover, the apparent applicability of the hard-collision model might be an artifact of the choice of fairly hard atoms in many of the early studies. There was, however, an experimental dilemma. In an ordinary gas sample there are few highly excited molecules so observation of their properties by any method other than detecting their reactions was virtually excluded. Solution of the problem was found by developing methods for production of nonequilibrium populations of excited molecules. All the methods involve rapid excitation, for example, by shock waves or by exposure to brief intense flashes of light (flash photolysis). An especially ingenious method for production of molecules in highly activated states makes use of synthesis from highly reactive fragments. For example, molecules of ethane can be produced in high, but variable, states of excitation by the following three reactions:



$$2\ H_3C\cdot \longrightarrow C_2H_6^{*}\ (\text{Internal energy}=3.7\ \text{eV})$$

$$H_2C\colon + CH_4 \longrightarrow C_2H_6^{*}\ (\text{Internal energy}=4.0\ \text{eV})$$

$$H\cdot + H_3C{-}\dot{C}H_2 \longrightarrow C_2H_6^{*}\ (\text{Internal energy}=4.3\ \text{eV})$$

Given methods for production of molecules in nonequilibrium high-energy states, one can study energy transfer by observing the return of the system to energy equilibrium. The process of deactivation in competition with decomposition, shown in Reaction (1), page 6, gives an accurate picture of the energy exchange processes with highly excited molecules. Some of the results are in striking disagreement with the implications of the simple Landau-Teller theory. For example, collision of iodine atoms with highly excited diatomic molecules can result in loss of more than one quantum of vibrational energy per encounter. Not only are relatively large amounts of energy transferred with significant efficiency but heavy atoms are more effective than light atoms as deactivators. Although the measurements are made by observing deactivation processes, the principle of microscopic reversibility demands that the reverse process—the donation of large amounts of energy to molecules which are already highly excited—must also occur. Although the probability of addition of more than one quantum of vibrational energy during an encounter is not high, it is sufficient to be very important in helping a molecule to climb the last part of the ladder leading to the top of a potential barrier.

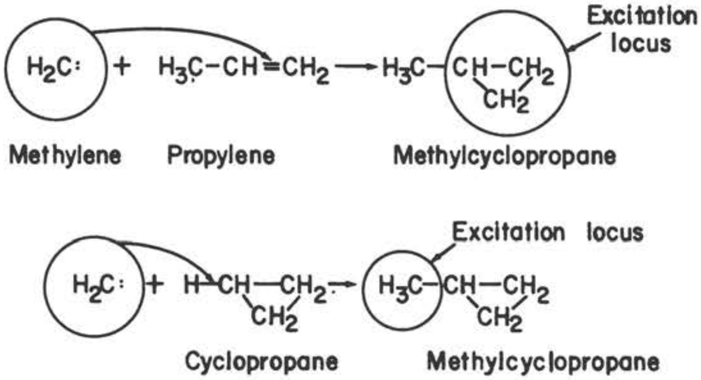
The new experimental results demand new theory. Quantum-mechanical calculations, with fewer mathematical approximations than the Landau-Teller theory, have been performed. They have assumed linear collisions of a marble (a hard atom) with a simple spring (a vibrating molecule). The calculations indicated an appreciable probability of transfer of several quanta of vibrational energy per collision. Logically, however, true collisions between real chemical species should be three-dimensional and somewhat soft and sticky. Extension of the analysis to three-dimensional models and introduction of "stickiness" into the collision still preserves the features of appreciable probability of transfer of large amounts of energy per collision. At present there is a need to extend the calculations to include complex molecules and molecules containing large amounts of vibrational energy.

Intramolecular Energy Transfer

As much new work is being devoted to the flow of energy within molecules as has gone into the study of the problem of getting energy into and out of molecules. Once again, experiments have indicated the inadequacy of the "simplest" theory and have guided development of extended theory that now seems promising.

The Slater theory is based on the premise that the vibrational energy of molecules can be treated as localized in sets of independent oscillators. The model views a molecule as if it were a set of springs, of varying sizes and strengths, connected so loosely that they vibrate without interaction. The model is useful for understanding some properties (such as infrared absorption spectra) of molecules. However, there is no guarantee that the interaction between various vibrational modes is not strong enough to permit transfer of energy among the various oscillators at a rate that is fast compared with intermolecular energy transfer. The different model of Rice, Rampsperger, Kassel, and Marcus (RRKM) begins with the premise that there is fairly strong coupling of at least some vibrations. In the extreme, this model becomes the same as a bedspring, where the individual coils are attached to each other by a strong, but flexible, framework. If one of the coils of a bedspring is plucked, the resulting vibrational motion will be rapidly spread over the entire network. Redistribution of the energy put into the bedspring corresponds to the internal relaxation process inside a newly excited molecule.

Within the past 5 years, experimental data have established the practical accuracy of the RRKM model. By practical, we mean that excess energy put into molecules by chemical activation appears to reach complete internal equilibrium at a rate that is rapid in comparison with the rate of intermolecular energy transfer. The point is illustrated by the ingenious work of Butler and Kistiakowsky with highly activated molecules of methylcyclopropane formed by two different reactions. The methods of production suggest that the excitation should originally be located in different parts of the newly formed molecules.



Both kinds of hot molecules showed the same range of reactions, indicating that internal redistribution of the excitation energy was much faster than deactivation by collision with other molecules.

Instructive computer experiments are also in progress to investigate the intramolecular energy-transfer problem using a variety of initial assumptions concerning the coupling between various molecular motions. Only simple models have been used so far but the work can be extended to large molecules, if the required large amounts of computer time can be financed.

The method of molecular beams offers a broad range of opportunities for new experiments. Two beams of atoms or molecules traveling in straight lines at known speeds can be crossed. Collisions between components of the two beams result in changes in velocity and in direction of flight of the particles. The scattered species can then be studied separately. The condition of the molecules immediately following an encounter tells the story of intermolecular energy-transfer; the redistribution of internal energy can be followed thereafter. These experiments, which seem to pry into the private lives of molecules in almost indecent detail, are not easy to engineer. Success depends upon the use of high-vacuum chambers so that results will not be confused by multiple collisions. The chambers must be large in order to accommodate the equipment needed to produce and detect the beams. Furthermore, "watching" the change in molecules requires the use of instrumentation that is delicate, ingenious, and costly.

Another experimental technique for the study of unimolecular reactions is mass spectrometry. The general method has been around for many years. Molecules are bombarded with electrons in a high-vacuum chamber and, due to energy transfer between electrons and molecules, electrons are knocked out of the molecules. The resulting molecular ions can be sorted according to size (mass analyzed). The process is complex because usually the ions formed originally break up into smaller ones, producing a complex mass spectrum. The fragmentation processes are examples of unimolecular reactions and the amount of energy with which the molecular ions are born can be controlled to some extent by varying the energy of the bombarding electrons. Recent major advances involve improvement in sensitivity and discrimination in detecting various products and depend on the conviction of chemical dynamicists that the highly complex fragmentation behavior of even large molecules is amenable to precise, systematic interpretation.

BIMOLECULAR REACTIONS

A large portion of elementary chemical reactions, including all processes in which large molecules are built from smaller ones, are bimolecular. These reactions are more complex than unimolecular processes. The problem of energy flux can no longer be separated neatly into intramolecular and intermolecular components since chemical change occurs during encounters between two species. Furthermore, the chemical changes, bond breaking and formation of new bonds, are likely to be much more complex than those occurring in unimolecular reactions.

The following are examples of rather simple bimolecular reactions. The first is one of the steps in the chain reaction by which hydrogen and chlorine react to give hydrogen chloride. The second is a prototype for one of the reactions that occurs in the formation of smog.

$$(1) \quad \underset{\substack{\text{Hydrogen}\\ \text{atom}}}{H\cdot} + \underset{\text{Chlorine}}{Cl_2} \longrightarrow \underset{\substack{\text{Hydrogen}\\ \text{chloride}}}{HCl} + \underset{\substack{\text{Chlorine}\\ \text{atom}}}{Cl\cdot}$$

$$(2)\quad \underset{\substack{\text{Hydrogen}\\ \text{atom}}}{H\cdot} + \underset{\substack{\text{Nitrogen}\\ \text{dioxide}}}{NO_2} \longrightarrow \underset{\substack{\text{Free hydroxyl}\\ \text{radical}}}{HO\cdot} + \underset{\substack{\text{Nitric}\\ \text{oxide}}}{NO}$$

Both reactions have intrinsically useful features. Hydrogen atoms, the simplest possible chemical species, are fairly easily produced by several methods; the other reactants and the products have ir spectra, arising from vibrational energy changes that are well known. Both reactions occur with fast rates minimizing competition from other chemical changes.

The minimum requirement for occurrence of any bimolecular reaction is encounter of reactant molecules. Even very early work showed that there are other important energetic and probability factors. Partly by analogy to the results of first-approximation rate theory used in considering unimolecular reactions (page 9), the following rate law provides a working hypothesis for treatment of a bimolecular reaction between a pair of unlike molecules, X and Y:

$$\text{Rate} = N_X N_Y A e^{-E^*/kT},$$

where

N_X and N_Y = concentrations of X and Y molecules,
A = number of collisions per concentration unit times a probability factor,
E^* = the activation energy for the reaction,
k = a fundamental constant, and
T = absolute temperature.

The equation is in agreement with most experimental observations. The reaction rate depends properly on the concentrations of X and Y molecules and the rate changes in the expected way as the temperature is varied. However, the value of A is often found to be far smaller than the number of collisions between molecules having a total translation energy greater than E^*. The question arises whether the value of A can be understood by taking into account inefficiency arising from differences in the angles of approach, the fact that the masses of X and Y are unequal, or other significant factors. The problem now appears to be solvable experimentally by use of molecular beams. For example, Greene and Ross have crossed a beam of potassium atoms (energy-selected) with hydrogen chloride molecules. They found a sharp increase in the probability of reaction ($K + HCl \rightarrow KCl + H$) when the relative translational energies of the atoms were raised to a high enough level to produce the product (KCl) in a vibrationally excited state. This shows conclusively that the reaction rate, even in such a simple system, is controlled by factors in addition to the "billiard-ball" mechanism of collision. Experiments with crossed molecular beams are only in their infancy but the early results indicate that the field should expand rapidly. Until recently only a relatively small number of products could be detected, but this limitation is being removed by the use of mass-spectrometric detectors. In principle, all the most important experiments can now be carried out. Complex reactants can be used and the products can be analyzed for total energy and state of vibrational and rotational excitation. Although this statement is not quite as fatuous as saying that all science is implied in the principles of quantum mechanics, we are still a long way from being able to carry out in practice all the experiments, or even the cream of the crop. The equipment required for the most primitive beam experiments is expensive and the costs will increase, although not without limit, as more complicated systems are tackled. However, we have a genuine feeling of urgency about pushing on. The first experiments have shown that "billiard-ball" kinetics become inadequate with even the simplest molecular systems. The behavior of complex molecules, which is really the heart of chemistry, is probably considerably farther from the predictions of classical theory.

A great deal of fine work has been directed toward locating the energy carried away by reaction products. For example, Polanyi has measured the infrared radiation from hydrogen chloride formed in the reaction, $H + Cl_2 \rightarrow HCl + H$. The results show that some of the molecules of hydrogen chloride are born in vibrationally excited states. A number of investigators have recently studied rates of reactions in which atoms combine to give diatomic molecules. The product of such a reaction is inevitably formed in a highly energetic state. In fact, unless a portion of the energy released in bond formation is carried away by some third body, the molecules will inevitably shake apart. The overall process, therefore, is much more complex than one might suppose and the reaction must be formulated as follows:

$$\begin{array}{ccccccc} 2X & + & M & \longrightarrow & X_2^* & + & M^* \\ \text{Atoms} & & \text{Third} & & \text{Excited} & & \text{Energy-rich} \\ & & \text{body} & & \text{molecule} & & \text{third body} \end{array}$$

The atoms are usually formed by flash photolysis or by shock waves. Since the probability of three small balls colliding simultaneously is negligibly small under usual conditions, classical collision kinetics predicts exceedingly low rates for the recombination processes. Experimental rates are faster than predicted, again indicating that atoms do not behave as hard balls in collision. For example, Davidson has studied the recombination of iodine atoms ($2I \rightarrow I_2$) in the presence of argon. The results indicate formation of iodine - argon complexes (I - Ar) having finite lifetimes. Whether the phenomenon should be called compound formation with a supposedly inert element (Ar), or should be described as a sticky collision, is an interesting semantic problem. The question of interactions involving atoms that do not become permanently bonded is inescapable and of prime importance.

Ingenious use has been made of mass spectrometers (page 14) for the study of bimolecular reactions of positive ions ($A^+ + BC \rightarrow AB^+ + C$). The reactions have fantastically high rates with cross sections* for reactions of the order of several hundred square angstroms, much larger than the diameters of the molecules would suggest. The results can be accounted for by assuming that BC is strongly polarized by the electric field of A^+ and attracted to it from relatively large distances. However, this certainly increases the fuzziness of ideas regarding the nature of molecular collisions; there may be many other instances in which molecules should be considered to be in contact even though "billiard-ball" mechanics would say only that they are close to each other.

An important, untapped area is the study of bimolecular reactions of vibrationally excited molecules. We know that reactions such as $A + BC \rightarrow AB^* + C$ may preferentially produce molecules in vibrationally excited states. The principle of microscopic reversibility demands that in the reverse reaction ($AB + C \rightarrow A + BC$) AB molecules will be exceptionally reactive if they are vibrationally excited. The generality of the effect needs to be tested by direct observation. Production of large numbers of vibrationally excited molecules is not easy, but can be done. Chemical activation (page 11) can be used in a way matching that used in the study of unimolecular reactions of hot molecules. Elegant molecular beam experiments can also be designed to do the job in more refined and systematic work.

Assessment of the importance of special quantum effects in bimolecular reactions has the same significance as with unimolecular processes (page 7). Both theoretical work and experimental work are now being devoted to the matter. For example, Johnston has estimated "tunneling" effects in reactions involving the transfer of hydrogen atoms, $A + HB \rightarrow AH + B$. Tunneling occurs when the probability of reaction increases because of quantum-mechanical uncertainty in the positions of the atoms and should be most pronounced with hydrogen, the lightest atom. Experimental tests are available from the study of the relative rates of transfer of the three hydrogen isotopes.** A simplified quantum-mechanical calculation for the reaction, $H + H_2 \rightarrow H_2 + H$ in a linear collision has been made by Rubin and Mazur. They conclude that tunneling may increase the rates of exchange as much as fivefold in comparison with those expected on the basis of classical models. More work is

---

*The cross section is the effective target area that the molecules present as they approach each other.

**Allowance must also be made for variations in rate arising from the difference in the vibrational energies of isotopic compounds.

needed to establish the conditions under which classical mechanics is inadequate for describing reacting systems. However, it is presently indicated that classical mechanics will do a remarkably good job in describing most reactions. This is certainly a cheerful note since the classical mechanical problem, though a formidable one, is less so than the one in quantum mechanics.

THEORETICAL FOUNDATIONS

In principle, the results of all experimental measurements on elementary unimolecular and bimolecular reactions can be predicted from fundamental theory. These reactions are completely described by quantum mechanics. In a similar vein, all questions of molecular structure can also be answered by solving the appropriate quantum-mechanical equations. Although these statements are true in principle, they have not yet become a reality in practice. The several computer calculations mentioned above are attempts to find ways to make such predictions.

Just as the problems of molecular structure (such as the calculation of bond distances and bond angles) can be described by the time-independent Schrödinger equation, the problems of elementary reaction probabilities can be described by the time-dependent Schrödinger equation. The introduction of time makes these latter problems much more difficult. The basic formalism necessary to treat reaction-rate theory from first principles has received careful attention from chemical dynamicists in recent years. For example, Golden has shown how to give an adequate quantum-mechanical characterization of reactants and products. Hirschfelder and Eliason have shown the relationship between reaction-collision cross sections and rate constants, and the equivalence between this formulation and absolute rate theory; the reformulation will be useful in relating the results of crossed molecular-beam experiments with those of bulk gas-phase reactions. Ross and Mazur have investigated the statistical mechanical problems associated with bimolecular reactions and have shown in a formal way that the usual bimolecular reaction rate law is a first-order approximation to the solution of a Boltzmann equation used to describe an irreversible chemical process. Higher-order solutions require that the rate constant be a function of time.

At present, the formal aspects of reaction rate theory, such as that of Eliason and Hirschfelder, are fairly well understood. The most difficult problem is the calculation of reaction cross sections. This problem can, in many cases, be separated into two simpler ones: (a) that of the intermolecular and intramolecular interaction forces among reactants and products (potential energy surfaces), which is due mainly to the quantum-mechanical behavior of the electrons for fixed nuclei, and

(b) that of the motion of the nuclei due to these forces. The first is essentially a problem in time-independent quantum mechanics and the second in time-dependent classical mechanics. Since several approximate analytical schemes for solving these problems have not been quantitatively successful, the direction of progress seems to be toward use of computers for calculations on simple systems. With the insight gained, more successful analytical theories of reaction cross sections are likely to be developed.

CONCLUSION

In summary, encouraging progress has been made in recent years on the detailed understanding of elementary reactions. The information to be obtained is comparable in its degree of detail with that which physicists have obtained in the study of nuclear reactions. Our goal is to be able to predict quantitatively the results of experiments. Although this is ambitious, we believe it is achievable.

Apart from the gain in fundamental understanding, which is a worthy end in itself, the sought for level of knowledge will have a great impact on the chemistry of all systems, whether involving atoms, radicals, ions, or molecules, in which the complex processes occurring may be broken up into an ensemble of simple elementary steps. Such processes pervade all of inorganic, organic, and biological chemistry as well as a multitude of technical applications. They include, among others, the processes that might have occurred in the earth's primordial atmosphere as a first step in the long path leading to the development of life.

III

SURFACE CHEMISTRY

Chemical reactions take place in all states of matter—solid, liquid, and gaseous—and many of the most important reactions occur at surfaces separating two different states, such as gas - solid, gas - liquid, or liquid - solid. Among these are such important processes as corrosion of metals, photosynthesis in plants, respiration in animals, hydrogenation of fats, and synthesis of gasoline.

Reactions in condensed phases (solid and liquid) are much harder to dissect into sets of elementary processes than are gas-phase reactions (Section II); reactions in heterogeneous systems containing two or more phases are still more difficult to analyze. Some heterogeneous reactions occur within one of the phases and therefore are similar to homogeneous reactions, except that some products or reactants are stored in an inert phase. However, in many cases the critical elementary processes occur at surfaces; some reactions cannot be carried out at all in homogeneous systems, indicating that unique molecular configurations exist at the surfaces.

An attempt to discuss all phases of current meritorious work with surface chemistry would be entirely too long for this presentation. We shall only sample the field by discussing the two subjects of heterogeneous catalysis and electrochemistry. Current work in the former field emphasizes interaction of gases with solids* and the latter field serves as a bridge between surface and solution chemistry. Both fields have vastly important implications for chemical technology.

*Many heterogeneous catalytic processes involve adsorption of liquids on solid catalysts.

HETEROGENEOUS CATALYSIS

In a heterogeneous catalytic process gaseous and/or liquid reactants are brought into contact with finely divided solid catalysts. Molecules of the reactants are adsorbed on the catalytic surface where they undergo various unimolecular and bimolecular reactions; the products are then desorbed and replaced by more molecules of reactants. Most of the critical reactions of petroleum chemistry are implemented by solid catalysts, and the reaction of hydrogen with liquid vegetable oils to form solid, synthetic fats is a well-known commercial process. A measure of the industrial importance of heterogeneous catalysis is the wholesale value of products of heterogeneous catalytic processes; in the United States the figure was $21.4 billion in 1962.* In addition, solid catalysts play central roles in such varied processes as the chemistry of evolution of life, the control of automobile exhaust, and the development of life support systems in space missions.

One good reason for considering heterogeneous catalysis as a separate phase of chemical dynamics is that, any effort to dissociate theory from practice in this field has so far proved futile. Catalytic processes characteristically come about through development and research, not research and development. The pattern has not changed much; industry first perfects a new catalytic process through enlightened empiricism. The information is then fed back to the theorist who endeavors to find an explanation. New concepts are generated but, before the existing process has been fully elucidated, the industrial chemist and the chemical engineer are already working on a new catalytic venture. The methods used in each cycle are still empirical, but somewhat less so than in the previous venture.

In this fashion, questions are being accumulated more quickly than answers. In the past, practice has tended to forget its great debt to the guidance of theory, but the situation is now changing rapidly because, for the first time, the designer of new processes is in a position to use a theoretical framework as a source of new inspiration. Although the theory will remain incomplete for the foreseeable future, the extent to which it will supply guidance will surely increase.

An example is the catalytic oxidation of naphthalene, a material abundantly available from coal tar, to phthalic anhydride, a valuable substance used in manufacturing plastics. The process is complicated by overoxidation to produce maleic anhydride and gaseous products, notably carbon dioxide. Because of the heat produced by the reaction, and its rapidity, the chemistry is coupled with transport phenomena that must be known and controlled. The desired product must be rapidly

---

*Report of a Survey Conference on Heterogeneous Catalysis, National Academy of Sciences—National Research Council, Washington, D. C. (1964), p. 1.

removed from the reaction zone before it is burned up. These disturbing physical problems must first be eliminated or understood. This is no mean task and much imaginative work will have to be done in this area, combining transport phenomena and fluid mechanics coupled to chemical dynamics.

After the uncoupling has been achieved, it will then be tempting to try to optimize the process by means of a kinetic analysis that should reveal the various parallel and consecutive reactions; that is, the reaction network leading to desired or undesired products. This has been attempted many times and more recently in greater depth with the help of digital and analog computers. However, the best information that can now be fed to computers is of questionable validity since the best data available are rate constants for competitive reactions which are themselves complicated networks of (unknown) elementary processes. In short, too many variables are unknown and the significance of the results, outside the range covered by actual experiment, is always questionable. Perhaps the greatest promise of computer technology lies in applying it to the handling of more detailed data concerning the kinetics of elementary processes and other important physicochemical data, as they are accumulated.

A relatively simple example of a catalytic reaction is the synthesis of ammonia as practiced on an industrial scale since 1912.

$$N_2 + 3H_2 \xrightarrow[\text{Catalyst}]{\text{Iron}} 2NH_3$$

The following set of reactions may well be responsible for the over-all process:

$$\begin{aligned} N_2 &\longrightarrow 2N_a \\ H_2 &\longrightarrow 2H_a \\ N_a + H_a &\longrightarrow (NH)_a \\ (NH)_a + H_a &\longrightarrow (NH_2)_a \\ (NH_2)_a + H_a &\longrightarrow (NH_3)_a \\ (NH_3)_a &\longrightarrow NH_3 \end{aligned}$$

In these reactions, subscript "a" denotes a species adsorbed at the surface of the solid catalyst. If specific rate constants, and their dependence on temperature, were known for each of the steps, the behavior of the system could be calculated for any set of reactor conditions.

Resolution of the over-all network into its component reactions and the dissection of each reaction into its elementary steps constitute a discipline that may be called applied chemical kinetics, chemical process kinetics, or chemical reaction design. The latter term implies that the knowledge thus accrued can be used to optimize the process by intelligent choice of the kinetic parameters.

Applied chemical kinetics has been practiced for a long time, but it is only recently that it has emerged as a separate discipline. The first textbook in the field by a group of chemists at the University of Louvain and the French Petroleum Institute was published in 1958.* The rapid acceptance and growth of this new discipline are stimulated by the needs of chemical engineering kinetics. Only after the dissection of the process has been completed is it possible to reassemble the elementary steps into component reactions and the latter into the over-all network. So it can be seen that the entire program leading to the optimization of the chemical plant rests, in the last analysis, upon an adequate knowledge of the chemical dynamics of elementary steps.

The following will demonstrate that our knowledge of elementary steps in heterogeneous catalysis is inadequate but that major advances are now being made in an exciting period of renaissance.

The Elementary Steps at Solid Surfaces

As in the synthesis of ammonia, there are two kinds of elementary steps for reactions catalyzed by solids. There are the primary acts of adsorption and desorption ($N_2 \rightarrow 2N_a$) and the steps involving chemical reaction of adsorbed species ($N_a + H_a \rightarrow (NH)_a$).

The need to understand these two kinds of steps calls forth many questions to be answered experimentally and generalized with the aid of theory. When molecules strike a surface, how many are scattered in a random manner and how many are reflected specularly (like light from a plane mirror)? When a molecule strikes a surface, how much energy is exchanged with the solid? What is the probability that a striking molecule will be adsorbed on the surface? How are adsorbed molecules bound to the surface? Are they bound at special locations and, if so, what is the nature of active centers? Are active sites in any way like the faces of perfect crystals or are they imperfections? What is the nature of the barriers to reactions at surfaces? What kind of probability factors influence internal and external energy transfer involving adsorbed molecules? Are the answers to such questions related to the answers being obtained in studies of elementary reactions

---

*J. C. Jungers, ed. Cinétique chimique appliquée, Société des Editions Techniques, Paris (1958).

in gas phases (Section II)? What is the importance, if any, of the collective properties of the solid on the chemistry of molecules adsorbed on its surface? For example, are the mobile electrons in a metal involved in reactions occurring at its surface?

Such questions have been asked for at least 40 years and many partial and speculative answers have been given. The whole arsenal of experimental tools available to chemists has been brought to bear on the subject. There have been many studies of the rates of catalytic reactions and a great deal of work has been devoted to characterization of adsorption of chemically unreactive materials on solid catalysts. The absorption spectra of adsorbed molecules, the magnetic behavior of catalysts with and without adsorbed species, the electrical properties of catalysts, and many other properties of the systems have been studied. Several tremendously important techniques come from such work. A spectacular example is the method for measurement of surface areas of finely divided solids developed by Steven Brunauer, Paul Emmett, and Edward Teller in the course of their work with the synthesis of ammonia (page 22). Many fundamental concepts of lasting value have also developed. For example, the process known as activated adsorption has been well characterized. Whereas in physical adsorption molecules go onto and come off surfaces at rapid rates, activated adsorption can be slow and occurs at rates which increase with increasing temperature. Obviously the process of adsorption itself can become a complicated problem in chemical dynamics!

Another area of important progress has been correlation of reactions on heterogeneous catalysts with related reactions carried out in homogeneous systems, especially in solution (Section IV). In some cases, the great similarities make it virtually certain that key elementary steps are identical. Consequently, some of the generalizations drawn from study of reactions carried out in the simpler, homogeneous systems can be transferred with considerable confidence to discussion of heterogeneous systems. Such procedures have produced interesting islands of insight in otherwise murky waters. Unfortunately, the mileage that can be got from such associative methods is clearly limited. One is forever arriving at the conclusion that A will surely react to give B rather than C, if it gets a chance to do either. Missing bridges connecting the islands to theoretical mainlands must be supplied by study of heterogeneous reactions themselves.

A New Look at New Surfaces

Until rather recently, all fundamental work has been stymied by the necessity of working with "dirty" surfaces. One can know in intimate detail the internal structure of a crystalline solid without having more than the foggiest notion about the structure or even the composition of the first layer of material which constitutes the surface. The reasons for this dreary situation are obvious. Consider a crystal of a pure metal such as nickel or platinum. The crystal is held together by strong bonding forces between neighboring atoms so that the entire crystal is really a giant molecule. Now imagine slicing through the crystal in order to create two new surfaces. Since the surfaces can be created only by breaking bonds between atoms, the new surface is a raw mass of unsatiated chemical affinity and is highly reactive. Exposure of such a surface to substances such as oxygen, nitrogen, or water, normally present in air, leads to extremely rapid reaction forming an entirely new surface of unknown structure and composition. Our total ignorance of the nature of the reaction medium assures that work with any such surface will be grievously uncertain at the most fundamental level.

The recent advent of new techniques for obtaining, maintaining, and measuring ultra-high vacua has made it possible to work with "atomically clean" surfaces for the first time. The consequent increase in significance of all studies of the interaction of gases with solid surfaces is almost staggering. A fairly good idea of what the target looks like enables one, using the craftiest tools of the trade, to make new sense from the results of studying energy changes when molecules are bounced off a surface. When a molecule sticks to the surface the atomic glue that holds it can be discussed in terms of familiar concepts of molecular structure. When the infrared spectrum of an adsorbed species is seen, it can be stated whether it has anything directly to do with a catalytic reaction. With dirty surfaces one never knew whether the phenomena being observed occurred at active sites or at totally inert places.

Along with ultra-high-vacuum techniques have come some fine new tools for the study of molecules on solid surfaces. Perhaps the most spectacular is field-emission microscopy, invented and developed by Müller at The Pennsylvania State University. This method makes it possible to actually observe the perigrinations of adsorbed atoms or molecules as they wander across the tip of a single clean crystal of tungsten metal. Another new and promising method has been developed by Germer at the Bell Telephone Laboratories. He has used scattering of low-energy electrons by adsorbed molecules to study detailed structures of the guest molecules. The method has long been used to study the structures of gaseous molecules but extending it to surface layers opens new doors.

The study of elementary processes at clean metal surfaces is fairly typical of much pioneering work in chemical dynamics. A rather large number of sophisticated methods must be brought into use in a single laboratory. The value of the special equipment in such a laboratory is normally several hundred thousand dollars and maintenance and improvement require sustained investment. Obviously, research at such a level will be economical only if the efforts of at least 10 to 15 research students and postdoctoral fellows are involved.

Not all researchers interested in heterogeneous catalysis will under-take intensive study of interactions of molecules with ultra-clean surfaces. However, reports of work with atomically clean surfaces will stimulate and guide the activity of those who continue to work with more complex, dirty systems which are, after all, of primary interest in the design of large-scale chemical operations. Chemical dynamics characteristically spreads new methods and new ideas throughout the field.

Finally, it should be noted that work with pure metallic surfaces is only one of the many important problems in heterogeneous catalysis. Cracking and rearrangement of hydrocarbons, key steps in the conversion of crude petroleum to high-grade gasoline, are carried out by using mixed metallic oxides as catalysts. Oxidation reactions, another group of important industrial processes, obviously cannot be carried out in oxygen-free environments. One of the most important new catalytic reactions to be discovered in recent years, the polymerization of propylene and similar hydrocarbons to geometrically ordered high polymers, is carried out through the agency of solid compounds formed by precipitation upon admixture of fairly complex liquid mixtures. Since no one yet knows how to prepare such catalysts with clean surfaces, the importance of the materials demands their intensive study in the unclean state.

ELECTROCHEMICAL DYNAMICS

Electrochemistry deals with the chemical changes accompanying passage of an electric current through a solution, as in electroplating, or the reverse process in which a chemical reaction is used as the source of energy to produce an electric current, as in a battery. Every student of high-school chemistry and physics has observed that a water solution of sodium chloride (salt) can be used to complete the circuit between the two terminals of a battery. Not immediately apparent, however, is the vast difference between the events that occur when the current passes through the solution and those involved when the current passes through the wires leading into the solution. The wires are metallic conductors through which electrons flow with very little resistance. In the solution, current is carried by charged particles known as ions. The changeover from electronic conduction to ionic conduction must occur at the interface between the solution and the wire; that is, at the surface of the electrode.* Electrons may be transferred from a negatively charged electrode (a cathode) to a species in solution, or electrons may be ripped out of molecules and donated to a positive electrode (an anode).

---

*Many materials other than metals may serve as electrode materials.

In both cases some molecule or ion from the solution undergoes an important chemical change. Separation of the cathode and anode is an obvious requirement in an electrochemical process; if they were in contact a short circuit would be created and the electrons would take the easy path of electronic conduction rather than entering the electrochemical process.

Electrochemistry is enormously important to mankind. We have already mentioned electroplating, which is used to apply smooth coatings to many metallic objects for both practical and aesthetic purposes, and the lead storage battery, which uses chemistry to provide electric current for starting our automobiles. Electrochemistry is also used in the production of vast quantities of useful chemicals and in a variety of systems for information, storage, and transmission. An active and potentially important area of research in many laboratories is development of fuel cells. The problem to be solved is direct conversion of energy released by a chemical reaction into electrical energy. Although efficiencies are still below practical levels, there is reason for optimism. Perfection of fuel cells would render steam generation of electrical power obsolete and would provide many other greatly desired amenities, such as exhaustless automobiles. Another futuristic project is development of a battery, based on molten salts, to be used as a power source in a hostile climate like that of the planet Venus.

Electrochemistry fascinates chemical dynamicists not only because of its inherent importance but because it provides precision tools for study of many other kinds of chemical reactions. Electrochemical methods provide some of the most precise monitors of reaction rates, both fast and slow, and often make possible controlled generation of chemical transients that are intermediates in complex processes. Two kinds of control of the driving force are, in principle, available. First, the intensity of the force is controlled by the potential applied to the electrodes. Second, the rate of the process can be varied by changing the current flowing in the system. Furthermore, much of the versatility of electrochemical techniques derives from the speed with which either potential or current can be varied.

The simplest type of electrode process involves the physical transport to an electrode surface of an electron acceptor (or oxidant) which receives an electron from the electrode and is thereby chemically changed to an electron donor (or reductant). The reductant is then transported from the electrode surface to the bulk of the solution. By modern electrochemical techniques, it is possible to measure or control rigorously the processes of mass transport, and therefore to focus attention upon the charge-transfer process.

In even the simplest electrochemical reaction some complications occur in detailed study of the process. At every interface between metal and solution there exists an electric double layer in which a layer of ions in the solution is more or less loosely associated with an opposite surface-charge in the metal. As electric charge is transferred between metal and solution the electric field of the double layer may act to accelerate or decelerate the charge-transfer step. An important question here is whether essentially all of the potential drop between electrode and solution occurs between the surface and the reaction site, or whether an appreciable portion extends beyond the reaction site into the solution. In the latter case, the residual potential drop either increases or decreases the probability of an ion appearing at the reaction zone. (See Figure 1.)

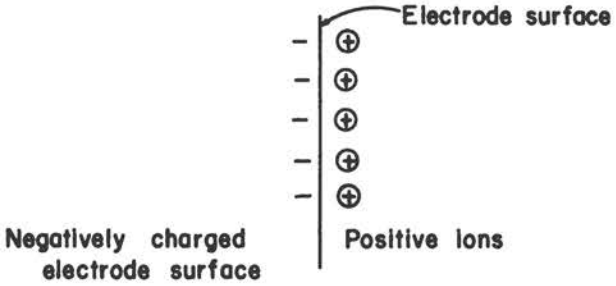


Figure 1. Double layer at a cathode

The mechanism of charge transfer to an electrode through the double layer has received considerable study since the 1930's by A. N. Frumkin in the Soviet Union and, more recently, by others, notably R. Parsons in England and L. Gierst in Belgium. There are many unexplored experimental areas, especially in nonaqueous solvents and in molten salts, where double-layer structure is still largely unknown.

Many questions remain concerning the elementary charge-transfer step that need theoretical as well as experimental study. Is quantum-mechanical leakage (tunneling) of electrons through the double layer important? Can tunneling of ions or molecules also occur? Is the simultaneous transfer of two electrons possible? What is the relationship between the structure of the surface of a metallic electrode and the structure of the subsurface metal? What is the effect of adsorbed layers of chemically inactive material on the electrode surface? Distinct progress toward some theoretical answers has been made in recent years, notably by R. A. Marcus in the United States and by N. S. Hush in England. An especially interesting approach involves correlation of charge-transfer reactions at electrodes with the rates of electron-exchange reactions in solution. Comparisons are made, for example, between the following processes:

$$\underset{\text{Ferrous ion}}{Fe^{2+}} \xrightleftharpoons{\text{electrode}} \underset{\text{Ferric ion}}{Fe^{3+}} + e^{-}$$

$$*Fe^{2+} + Fe^{3+} \longrightarrow *Fe^{3+} + Fe^{2+}$$

*Isotopically labeled.

The symmetrical electron-exchange process can be made detectable by isotopic labeling experiments.

Another level of complexity is reached when the electrode process involves chemical steps other than the primary charge transfer step. It is here that a great deal of effort has been exerted in recent years in the United States as well as abroad to create a whole arsenal of measurement weapons that is now available for use. Most important, it is possible through modern electrochemical techniques to generate active intermediates such as free radicals and unstable ions and to study the rates of appearance and disappearance of these species. Thus electrochemistry can serve as a powerful tool to study processes other than those occurring at electrodes.

A simple example of a secondary chemical step is the ionization of pyruvic acid, CH_3COCO_2H, prior to the reduction of its anion.

$$\underset{\text{Pyruvic acid}}{CH_3COCO_2H} \rightleftharpoons \underset{\substack{\text{Hydrogen}\\ \text{ion}}}{H^+} + \underset{\substack{\text{Pyruvate}\\ \text{anion}}}{CH_3COCO_2^-}$$

$$\underset{\substack{\text{Pyruvate}\\ \text{anion}}}{CH_3COCO_2^-} + \underset{\text{electron}}{2e^-} + \underset{\substack{\text{Hydrogen}\\ \text{ion}}}{2H^+} \xrightarrow{\text{electrode}} \underset{\substack{\text{Lactate}\\ \text{anion}}}{CH_3CHOHCO_2^-}$$

In Prague in 1947, Brdicka showed by means of polarography (electrolysis with the dropping mercury electrode) that the neutral molecule and the anion are reduced at different potentials, and that in principle the rate of ionization can be deduced from the relative currents for the two processes. However, a detailed quantitative interpretation became possible only in 1953 when Koutecky in Prague first solved the exact equations describing the interaction between diffusion at a growing sphere and the kinetics of homogeneous reactions coupled with charge-transfer reactions. Thus, the dropping mercury electrode has assumed new significance, beyond its obvious importance to analytical chemistry, because it is a tool for the study of reaction rates. In addition, it represents almost the only electrode known to be uniform, smooth, and clean (at least momentarily). Pulse techniques permit interrogation of a dropping electrode over such short time intervals (10^{-4} sec) that its growth rate is negligible. The significance of polarography was recognized in 1959 by the award of the Nobel Prize in Chemistry to Professor Jaroslav Heyrovsky of Prague, the originator of the method.

Other examples of more complex electrode processes are those in which a secondary reaction follows the charge-transfer step, or intervenes between two such steps. In addition, adsorption or rearrangement steps can impose rate limitations.

A valid field in its own right, electrochemistry is also now ready to make significant contributions to various other branches of chemistry. As a branch of surface chemistry, it can yield valuable information about the state of solid - liquid interfaces, although, of course, only those involving electrically conducting or semiconducting solids. By serving as a generator of unstable or transient species, such as intermediate oxidation states or free radicals, an electrode can serve as a tool to determine the lifetimes of such species or as a preparative device for study of these species by other methods, such as electron spin resonance. By supplying the most powerful known means of oxidation and reduction, electrochemistry offers entry into the study of unusual oxidation states. Its techniques can be applied under unusual or extreme conditions such as high pressure. It affords an avenue for the study of chemical dynamics in the intense field of the electrical double layer. Time is ripe for its significant contributions to the chemistry of living cells, particularly in the study of redox and membrane transport phenomena.

Electrochemical techniques are inherently adaptable to a wide variety of observations. By controlling the electrode potential, the rate of the charge-transfer step can be controlled. By controlling the geometry of the system and by using proper time-intervals for measurements, the mass transport rates can be controlled. By measuring the current, the instantaneous rate of charge transfer can be measured. There are factors, to be sure, which render the situation less straightforward than would appear from these simple statements. For example, any change of electrode potential involves the passage of current to charge or discharge the electric double layer. Any passage of current produces finite changes in concentrations at the electrode surface and a voltage drop through the solution because of electrolytic resistance. But by using special experimental methods, such as observations of short duration and voltage shifts of small magnitude, it is possible to eliminate the effects of these complicating factors and to focus attention upon the primary electrode reaction (charge transfer) and the secondary chemical processes in solution.

In electrochemical as well as in other methods of chemical kinetics, we may distinguish between two general approaches: the steady-state method and the nonsteady-state, or transient, method. In the steady-state method, all intermediates in the reaction scheme are at constant concentration because they are being formed as fast as they are being consumed. In the transient method, the concentrations of reactants change with time, although the time scale may vary over extremely wide limits.

A powerful new tool for the steady-state method in electrochemical dynamics resulted from the work of Levich of the Soviet Union in 1947, who applied the theory of mass transport to a rotating-disk electrode. By changing the rotation rate, the rate of diffusion can be changed in a predictable way, and over wide limits. Then, using the electrode potential to change the charge-transfer rate, it is often possible to make the secondary reaction-rates in solution control the rate of the over-all reaction, and to measure this over-all rate by the current. Thus, in a scheme such as

$$A + B \xrightarrow{k} C \xrightarrow{e^-} D$$

the substance C undergoes an electrode reaction, the rate of which is limited by the rate of formation of C and measured by the current. By applying a known and constant current, the over-all rate can be controlled, and if the steady-state concentration of C can be determined by some independent method such as color intensity, the rate constant k can be measured over wide limits.

In contrast to steady-state methods, transient or pulse methods are becoming increasingly important because they are adaptable to very rapid processes and because they produce a minimum of change in the system under study. Of the various short-time pulse methods now in use, mention should be made of the voltage-step method in which a current pulse is measured over a short-time interval of perhaps 10^{-6} sec; the constant current method in which the change of electrode potential is measured; and the impedance method, in which a small ac signal is applied to the electrode and the ac impedance is measured as a function of frequency. Still other techniques involve the application of a known quantity of electricity to an electrode and observing the change of potential with time; and the application of a high-frequency pulse under conditions of zero dc, to measure the small shift of potential due to the asymmetry of the electrode reaction. The trend is toward the use of more complex input signals, and correspondingly more complex read-out systems.

For all of these techniques, the availability (mainly since World War II) of electronic components of high sensitivity, stability, and reliability has been critical. Devices such as pulse generators, oscilloscopes, amplifiers, frequency meters, and digital voltmeters have reached such an advanced state of development that chemists with little background in electronics can readily make use of measurements that 20 years ago would have been extremely difficult if not altogether impossible.

The types of information obtainable from electrochemical measurements may be illustrated in more detail by the single, and relatively simple, technique of electrolysis at constant current. After applying a sudden electrolysis current, the observation of the rate of change of voltage can be done over a wide range of time intervals. In the microsecond range, the rate of voltage change is a direct measure of double-layer capacitance, useful in the study of double-layer structure as well as the surface state of the electrode. Thus processes such as the oxidation of a metal to form an oxide layer of a single atomic thickness, or even the formation of a small fraction of such a layer, can be studied. Again, the process of adsorption, or accumulation of foreign substances from solution at the surface, often markedly changes the double-layer capacitance. An important future field of enormous consequence to the chemistry of living cells would appear to be a study of adsorption at membrane surfaces. Development of an electrochemical method for such studies is a challenge for the future.

Other types of information can be sought by applying a smaller current, and making measurements over a longer time interval. The time interval immediately following double-layer charging (usually from 10^{-2} to 10^{-4} sec) is useful for a study of the rate of the charge-transfer process. We speak of the exchange-current density at equilibrium as a measure of the rates of the opposing electrode reactions that are equal at equilibrium. Only recently has it become possible to evaluate exchange current densities for rapid (reversible) electrode reactions. Much useful information about the structure and properties of chemical species (ions or molecules) in solution can be gleaned from a knowledge of the rates with which these species exchange charge at an electrode surface.

A still longer time interval (up to several seconds) is used to study the rate of diffusion of reacting species in solution. A simple technique to determine whether diffusion alone is occurring is to measure the so-called transition time at various applied currents. The transition time corresponds to the time necessary for a sudden voltage jump to occur, corresponding to the depletion of diffusing material at the surface. If diffusion alone occurs, the transition time varies in a known way with current, and diffusion coefficients, which are a measure of molecular or ionic size in solution, can be evaluated. Diffusion-controlled transition-time measurements also serve as a basis for quantitative analysis, because diffusion rates are proportional to concentrations. On the other hand, if a complicating factor such as a chemical reaction preceding the electrode process is involved, the variation of transition time with current permits an evaluation of the rate of the preceding reaction. Still other variations, such as the reversal of current after the passage of a known current for a known time, with or without a dead interval, allow the calculation of rates of secondary processes in solution.

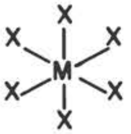
To summarize, electrochemists have made available a large variety of measurements for application to practical and research problems. Interconversion of electrical and chemical energy is of increasing technological importance. The methods serve all branches of science. Moreover, electrical phenomena are commonly associated with life processes, such as the action of the heart and the brain. The basic chemical nature of these phenomena is scarcely understood, but electrochemical measurements are certain to be highly significant in unraveling these and other complex chemical reactions of living things. Full exploitation of the field requires an intellectual climate favorable to pure research in which teams of investigators can work with the fundamentals of electrochemistry and exchange information and ideas with biologists, medical scientists, and synthetic and structural chemists.

IV
REACTIONS IN SOLUTION

A great portion of all chemical reactions involves complex molecules and is carried out in liquid solutions. The field is the backbone of functional chemistry. Control of such reactions is fundamental to the success of much of chemical industry and to the entire field of medicinal chemistry. It is the very basis of life processes. Furthermore, study of the mechanisms of such reaction systems has a history of continuous challenge and remarkable success; nowhere is the unique methodology that constitutes the genius of chemistry better demonstrated. The common use of solvents in chemical reactions is not merely a matter of accident or convenience; the solvent often absolutely controls the course of a reaction. For example, many compounds dissociate in solution to produce ions which may enter into reactions that are impossible for the parent molecules. Since the extent of such dissociation and the reactivity of the ions produced are both sensitive functions of the nature of the solvent, solution chemistry adds new dimensions of complexity and control that are unknown in the study of reactions in the gas phase.

The principles involved in the study of reactions in solution, outlined in the introduction, are identification of elementary steps and analysis of networks of competitive processes. The techniques of study are many and varied. Experimental measurement of reaction rates, from the very slow to the very fast, is of obvious importance, but many more subtle tools have also been developed. An example is the use of isotopic substitution which enables the chemist to trace the history of particular molecules or parts of molecules in one or more reactions. Perhaps the most interesting methodology is systematic variation of structure. To a casual observer the several million known compounds may appear to be an intangible chaos. To the chemist, however, the multitudinous array provides a tool of extraordinary delicacy for the study of reactions. The principal variables available to the physicist are energy and macroscopic physical design. In contrast, the chemist may vary the design of his system by tiny increments at the molecular level.

An example is the study of the dynamic behavior of a compound consisting of a metallic atom surrounded by an atomic matrix containing carbon, hydrogen, and oxygen atoms. In the following schematic diagram, the metal is represented by M and the attached groups by X's:



Such molecules undergo many reactions, including some in which the X groups are modified without becoming detached from the metal. The details of such reactions may be studied by conventional techniques. For example, one might conclude that a particular reaction involves development of a negative electrical charge on the group undergoing reaction. Such a theory can be tested by systematic variation of the electrical field provided by the central metal atom. One way to do this is to use different metal atoms such as cobalt, chromium, manganese, or iron in the compounds containing the same X groups and then to compare the behavior of the different molecules. The use of small systematic structural modifications to call up a variation in specific properties has frequently been decisive in indentifying elementary steps in complex reactions. The chemistry-oriented reader will realize that the variations will be even more subtle than is implied by the word "field" and that the comparison will not always be possible because of variation in the ease of breaking M–X bonds in the series of compounds.

To provide a picture of what has happened recently and what is likely to happen in the near future, we discuss briefly selected areas of active investigation. The subjects are chosen to illustrate general methodology, identification of elementary processes, and development of experimental techniques. Chemistry effected by radiation is also included because of widespread current interest in the subject.

SUBSTITUTION AND OXIDATION-REDUCTION REACTIONS OF METALLIC COMPOUNDS

Substitution Reactions

Substitution reactions of coordination complexes of metal ions have attracted the attention of investigators for more than 60 years. Metal ions bind (coordinate) a wide variety of chemical groups called ligands. Anions such as fluoride, chloride, bromide, iodide, sulfate, carbonate, cyanide, phosphate, acetate, and oxalate readily attach themselves to a large variety of metal ions. Also capable of coordination are neutral molecules such as water, ammonia, carbon monoxide, alcohols, and even hydrocarbons such as acetylene and ethylene. Such a variety of combinations makes possible an enormous number of reactions in which one coordinating group replaces another on a single metal ion. The full magnitude of the possibilities is appreciated only when it is recalled that of the 103 known elements of the periodic table, 83 are classified as metals.

Coordination compounds of metals play key roles in many important chemical processes. Hemoglobin, the red oxygen-carrier in blood, is an iron compound in which the iron atom is surrounded by a large polyfunctional ligand. Chlorophyll is a similar compound with magnesium as the central metallic element, and vitamin B-12 contains a cobalt atom in another complex molecular matrix. Metal complexes are involved in most electroplating processes and many of the most important catalysts used in synthetic chemistry are complexes of metals such as aluminum and titanium.

Study of the mechanisms of substitution reactions of coordination compounds provides a striking example of the mutual interaction and stimulation of the fields of chemical dynamics, structure, and synthesis. Synthesis of the compounds is a prerequisite, and knowledge of their structure an essential, for any serious study of reaction mechanisms. In turn the synthesis of many of the coordination complexes has depended entirely on a knowledge of the relative rates of displacement of ligands. On the other hand, the majority of the known structures of coordination complexes were first inferred from deductions about the changes in arrangement of the coordinated groups during the reactions used in the synthesis. While similarities and regular trends in rates are evident in many series of exchange reactions, there are also striking variations. For example, consider the rates at which a group of metal ions exchange water molecules in their coordination shells for other water molecules:

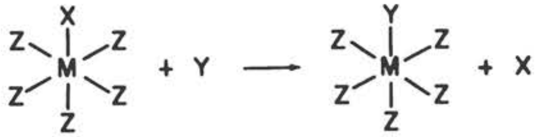
$$M(OH_2)_6^{n+} + H_2O \longrightarrow H_2O\,M(OH_2)_5^{n+} + H_2O$$

Special techniques (page 40) are obviously required to observe this symmetrical exchange reaction. The following are average times required for the exchange process:

Metal ion	Average exchange time
Cr^{3+}	1.4×10^5 sec
Fe^{3+}	3×10^{-4} sec
Mn^{2+}	3×10^{-3} sec

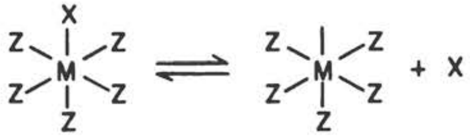
The difference in the rates of reaction of hydrated chromic (Cr^{3+}) and ferric (Fe^{3+}) ions is attributed to the fact that the two ions have different numbers and arrangements of their outer electrons. The difference between the reactivity of ferric and manganous (Mn^{2+}) ions, which have the same electronic configurations, is due to the difference in the nuclear charges. The source of the large differences in reactivity are understood in principle but cannot yet be quantitatively accounted for by theoretical calculations.

To illustrate the intimacy of the questions being asked about substitution reactions, we may consider replacement of one group, X, by another, Y, on a metal, M, having six groups symmetrically coordinated around it.

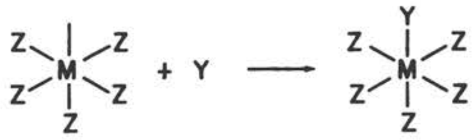


(1)

Two plausible reaction paths are evident. (a) The attached group X could first dissociate giving a fivefold coordinated species as an intermediate. The sixth position could then be filled in a subsequent reaction by the entry of Y, as



(2)



(3)

(b) The other possibility is that the attached group X will be displaced at the time Y makes its entry. In this case the displacement occurs in a single step and is represented by Reaction (1).

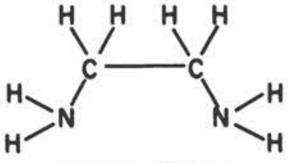
It may be asked whether every displacement reaction occurs by path (a) or path (b). In few cases is the answer known. Wilmarth and Haim have recently presented unequivocal evidence for the mechanism of a reaction of cobaltic ion coordinated with five cyanide ions and a water molecule. The water is displaced by azide ion, N_3^-, according to the net reaction

$$Co(CN)_5(H_2O)^{2-} + N_3^- \longrightarrow Co(CN)_5N_3^{3-} + H_2O. \qquad (4)$$

By studying the kinetics of the reaction, they established that at high azide-ion concentration the rate becomes independent of the azide-ion concentration. Such a result is inconsistent with path (b) but is in complete accord with path (a) if every time a water molecule is lost the fivefold coordinated intermediate picks up an azide ion in preference to a water molecule. Since capture of an azide by the intermediate is a bimolecular reaction, its rate can be increased by increasing the concentration of azide, and the over-all rate of reaction will then be limited by the rate of formation of the intermediate.

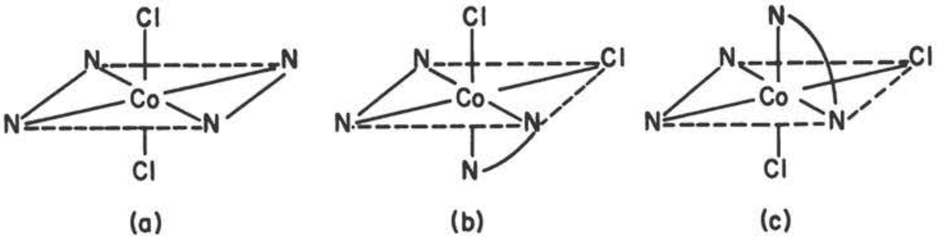
In most cases the kinetic data do not lead to such a straightforward conclusion. Thus the rate may not become independent of the concentration of the entering group, even at the highest concentrations attainable. Or the entering group may be attracted into the second coordination sphere of the coordination complex to form a stable outer-sphere complex containing an extra ligand. In such a circumstance, the rate will appear to be independent of the concentration of the entering group even though the reaction is proceeding by path (b). The latter possibility is unlikely in the case of reaction (4) because of the electrostatic repulsion between the like charges of the azide ion and the cobalt complex.

Another example of substitution on a coordination compound of cobaltic ion illustrates the use of subtle details to identify the precise course of a reaction. The probe used was changes in the stereochemistry (internal geometrical arrangement) of complexes. An excellent coordinating group giving rise to particular stereochemical effects is the molecule ethylenediamine.



Ethylenediamine

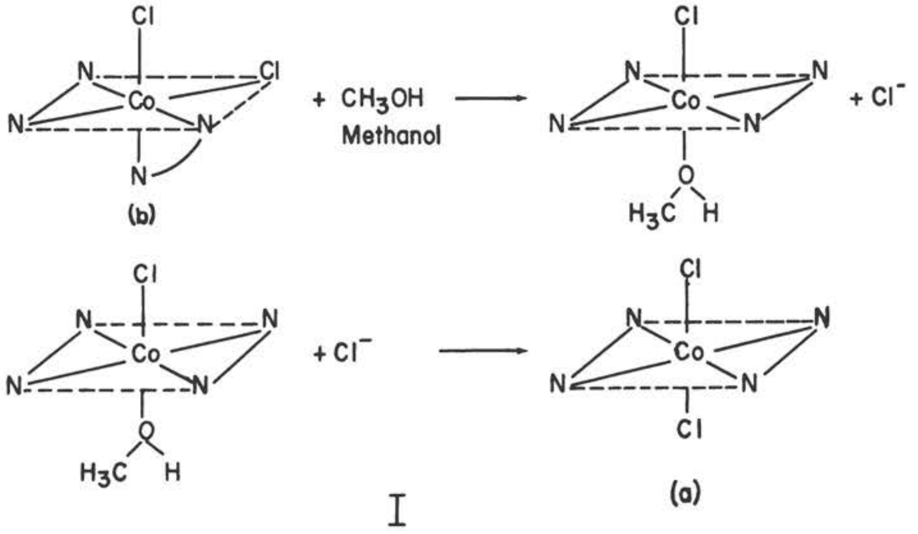
It attaches to cobalt through both of its nitrogen atoms and thus occupies two of the six positions around a cobaltic ion. These positions must be neighboring since the ethylenediamine molecule is too short to stretch from one position to that on the opposite side of the metal ion. Two ethylenediamines and two chlorides can form with cobaltic ion three coordination complexes, all having a net charge of +1.



Only the nitrogens of the ethylenediamine molecules are shown.

Species (a) has chlorides opposite each other while in (b) and (c) they are adjacent. The latter two are called optical isomers and differ only in that one is the mirror image of the other (reflected from top to bottom as drawn). Optical isomers are related to each other as a right hand is to a left hand.

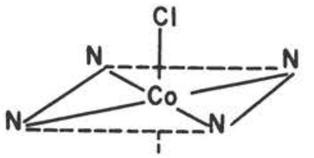
Starting with the species (b) in a solution containing chloride ion one can study the rate of conversion of (b) to (c) and of (b) to (a). Further, by labeling the chloride ions in the solution with radioactive chlorine, the rate of exchange of free chloride ions with the chlorides attached to the cobalt can be measured simultaneously. Brown, Ingold, and Nyholm, in early studies of this system in methanol as solvent, showed that the rates of conversion of (b) to (a) and (c) were precisely equal to the rate of replacement of chloride in the cobalt complexes by chloride ion in the solution, thereby establishing that these reactions occur by substitution. Further, Bosnitch and Tobe found that the rates were independent of the concentration of chloride ion at low chloride concentration—a result consistent with the two-step mechanism of reactions (2) and (3) involving a fivefold coordinated intermediate. Alternatively, however, the rate could be independent of chloride ion if the path followed were a slow reaction of the complex with the solvent methanol, followed by a rapid substitution of the methanol by chloride ion, e.g., for (b) reacting to (a) in I.



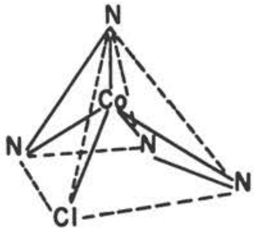
I

Recently Tobe and Bosnitch prepared and characterized the methanol compounds and showed that they do not react rapidly enough with chloride ion to account for the observed rate according to such a reaction mechanism. Therefore, the original conclusion is substantiated that reaction is by way of the fivefold, coordinated intermediate.

One may then ask what the geometry of the fivefold coordinated intermediate is. Information may be obtained from a comparison of the rate of conversion of (b) to (c) with the rate of chloride exchange for these species. The experiments showed that the rate of chloride exchange was just twice the rate of conversion of (b) to (c). These results indicate a fivefold coordinated intermediate that has lost its optical asymmetry so that the filling of the sixth position produces just as much (b) as (c). Thus the intermediate could have a symmetrical structure such as

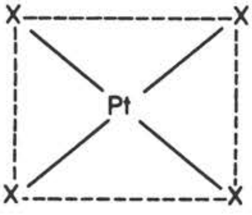


or



Alternatively it need not be symmetrical if it inverts its asymmetry much more rapidly than it returns to sixfold coordination. The exact arrangement remains a challenging problem.

The complexes of divalent platinum (Pt^{2+}) exhibit a coordination number of 4 with the attached groups arranged in a planar square around the platinum ion.



Rate laws for substitution of an X by Y are of the form

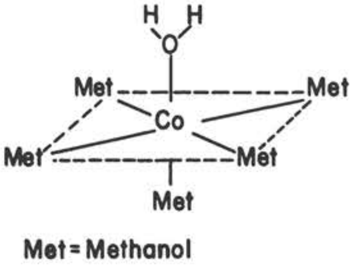
$$PtX_4 + Y \longrightarrow PtX_3Y + X$$

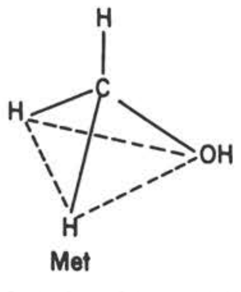
$$\text{Rate} = k_1[PtX_4] + k_2[PtX_4][Y]$$

where k_1 and k_2 are rate constants and brackets indicate the concentration of the enclosed species. In a number of cases the first term has been shown to correspond to replacement of one X by a solvent molecule, followed by the rapid replacement of the solvent by a Y group. The second term corresponds to direct replacement of an X by a Y without intervention of the solvent. When the four groups initially around the platinum differ, the configuration of the three remaining groups relative to each other is retained when a displacement reaction occurs. These results are all in accord with the idea that such reactions take place by the displacement of the X group as the Y group enters, rather than by dissociation to form an intermediate of coordination number three.

In most cases, answers have not been found to questions about mechanisms of substitution as detailed as those given above, either because the measurements have not been made or because the experimental difficulties are great. In particular, many metal ions exchange their coordinated groups rapidly, making even the rate measurements a formidable task. Recent developments in techniques of measuring fast reactions give promise, however, of making reactions of nearly any velocity accessible to study.

For instance, we may consider the substitution reactions of cobalt in an oxidation state different from that considered above, i.e., cobaltous ion (Co^{2+}). This ion exhibits rates of substitution that usually are faster by many orders of magnitude than those of cobaltic ion (Co^{3+}). Luz and Meiboom measured some rates-of-exchange reactions of this ion dissolved in methanol by observing the proton nuclear magnetic resonance of both the hydrogen attached to the oxygen of the methanol and the hydrogens attached to the carbon. By cooling the system well below room temperature, the rate of exchange of methanol molecules in the first coordination sphere of the cobaltous ion with those in the bulk of the solvent became measurable. For example, the average lifetime of a methanol molecule in the first coordination sphere is 10^{-3} sec at -10°C. Both types of protons gave the same rate, showing that the molecules exchanged intact; that is, the proton on the oxygen did not exchange with protons on other methanol molecules more rapidly than the whole molecules exchanged. With the addition of a small amount of water, the nuclear magnetic resonances of methanols in the first coordination sphere of the complex containing one water and five methanols could be observed.





Further, the rate of exchange of the methanol molecule opposite the water could be followed independently of the rate of exchange of the four methanols adjacent to the water. Such extensive knowledge of the private life of a molecule was undreamed of a few years ago.

The recent measurement of fast substitution reactions has sharpened our concept of metal ions in solution in a way that promises to aid greatly in future studies of such systems. Twenty years ago one spoke of hydrated ions in aqueous solution. Ten years ago there was some evidence of the number of water molecules coordinated to most metal ions. Today the time the species retains its identity is often known. Thus the chemical species aluminum ion, consisting of six water molecules surrounding the aluminum ion, remains intact for approximately 0.1 sec at room temperature, i.e., before one of the coordinated water molecules is replaced by another of the solvent. Ferrous ion is a similar species, but maintains its integrity for an average of only 5×10^{-8} sec at room temperature.

Oxidation-Reduction Reactions

Oxidation-reduction changes, constituting another large area of chemical dynamics, display an almost infinite variety of chemical reactions. All life depends directly on oxidation-reduction: the oxidation of organic matter in animal tissues and the fixation of carbon dioxide by plants. Electrochemistry exploits the separation of the oxidation process from the reduction process. Corrosion of metals and oxidation of paints are undesirable oxidation-reduction reactions. The manufacture of sulfuric acid, chlorine, and sulfur dioxide; the oxol process for the production of aldehydes and alcohols; the isolation of plutonium; and numerous other processes depend on oxidation-reduction.

Innumerable questions may be posed about oxidation-reduction reactions. For example, one of the major problems in life processes is whether oxidation-reduction reactions are consummated by electron transfer or by transfer of atoms or groups of atoms. Related studies of simpler systems in aqueous solution may be used to illustrate some of the questions that have been answered.

Consider the transfer of electrons between metal ions in solution. Two plausible paths by which the electron is transferred may be visualized: first, the outer-sphere path where the two metal ions maintain their first coordination spheres intact so that the electron must travel through both coordination spheres to complete the transfer; and second, the inner-sphere path where one metal ion loses one of its coordinated groups and becomes attached to one of the coordinated groups of the other metal ion—the so-called bridged activated complex. In the second path the electron needs to travel only through the single coordination sphere.

Some examples of both types of path are now well established. Thus the electron exchange between ferrocyanide ion and ferricyanide ion must occur by the outer-sphere path because the electron transfer takes place much more rapidly than either species exchanges one of its cyanides with free cyanide ion.

$$\underset{\substack{\text{Ferrocyanide}\\ \text{ion}}}{Fe(CN)_6^{4-}} + \underset{\substack{\text{Radioactive}\\ \text{ferricyanide}\\ \text{ion}}}{\overset{*}{Fe}(CN)_6^{3-}} \rightleftharpoons \underset{\substack{\text{Ferricyanide}\\ \text{ion}}}{Fe(CN)_6^{3-}} + \underset{\substack{\text{Radioactive}\\ \text{ferrocyanide}\\ \text{ion}}}{\overset{*}{Fe}(CN)_6^{4-}}$$

Taube and his co-workers first demonstrated in a striking fashion the existence of inner-sphere paths. By choosing an oxidizing agent that was quite inert to displacement of groups in its first coordination sphere, and a reducing agent that rapidly exchanged its groups but was inert to substitution in the oxidized form, the presence of a bridged activated complex was evident from the products. Thus when an aqueous solution of chromous ion was mixed with one of chloropentaminecobaltic ion the following reaction took place:

$$\underset{\substack{\text{Chromous}\\ \text{ion}}}{Cr^{2+}} + \underset{\substack{\text{Chloropentaminecobaltic}\\ \text{ion}}}{Co(NH_3)_5Cl^{2+}} + 5H^+ \rightleftharpoons$$

$$\underset{\substack{\text{Chlorochromic}\\ \text{ion}}}{CrCl^{2+}} + \underset{\substack{\text{Cobaltous}\\ \text{ion}}}{Co^{2+}} + 5NH_4^+$$

The Co(III) on the left and the Cr(III) on the right are similar in that they undergo exchange of coordinated groups only very slowly. The observation that the product Cr(III) contains a Cl^- in its first coordination sphere shows unequivocally that the chromium was attached to the chloride at the instant it changed from Cr(II) to Cr(III) by loss of the electron. Since the cobalt could not release the chloride until it became Co(II), both of the metal ions must have been attached to the chloride at the instant of transfer of the electron.

Although a number of both inner- and outer-sphere reaction paths are established, in the great majority of such reactions this question remains to be decided. Since the reacting ions and products are often labile, a criterion other than examination of the products will have to be developed. Another important question is the role of ligands in bringing about electron transfer in both the inner- and outer-sphere paths. It is known that the rates of transfer vary greatly with the nature of the coordinated groups and are remarkably large in some cases where the structure of the ligands makes them good conductors of electrons. Attempts have been made to calculate from first principles the rates of outer-sphere reactions, in which only electron transfer occurs—but with limited success. Marcus developed an impressive correlation between the rates of such reactions and the rates at which each of the individual partners transfers electrons to electrodes in electrochemical reactions (Section III).

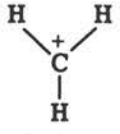
Substitution and oxidation-reduction reactions are by no means restricted to the metallic elements. Superficially similar changes are seen in the chemistry of elements such as carbon, phosphorus, sulfur, nitrogen, oxygen, boron, and the halogens. The reactions of carbon compounds have been studied extensively, as will be illustrated shortly. Mechanisms of reactions of the other nonmetallic elements have been largely neglected and merit much more attention than they have received in the past. The neglect is not really due to oversight. Considerable money, manpower, and time will have to be expended before the tools developed in recent years can be brought to bear on all problems where they are urgently needed.

TRANSIENT INTERMEDIATES

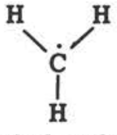
We have frequently alluded to the complexity of many reactions. In the previous section we showed that substitution reactions of metal ions bearing six ligands often proceed by way of short-lived pentacoordinated intermediates. Many reactions involve such transient intermediates. The over-all rates of reactions are often determined by the speed of formation of the transients, and the nature of the products is determined by reactions of the intermediates. Practical control of such reactions obviously depends on a detailed understanding of the chemistry of the intermediates. A fascinating set of examples was found during the study of substitution reactions of carbon compounds (organic compounds). Consider the substitution reactions of one-carbon compounds, the derivatives of methane:

$$H_3C{-}X + Y \longrightarrow H_3C{-}Y + X$$

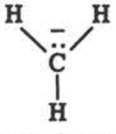
We now know that such reactions can proceed by way of no less than four distinctly different types of transient intermediates.* Three of the intermediate types contain trivalent carbon atoms and differ only in the number of electrons that they contain.



Methyl cation
(a carbonium ion)



Methyl radical
(a free radical)

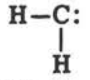


Methyl anion
(a carbanion)

---

*In addition, substitution may also involve only one elementary step, i.e., Y enters the molecule as X is leaving.

The fourth type of transient is an electrically neutral species formed by removal of two of the groups attached to carbon:



$$\mathrm{H{-}\underset{\underset{H}{|}}{C}{:}}$$

Methylene*
(a carbene)

The necessity for postulating all four kinds of fragments of carbon compounds was originally derived exclusively from studies in chemical dynamics. Observations concerning the kinetics of substitution reactions and the variation in rates in response to structure or even the nature of the reaction media led to the conclusion that these kinds of intermediates must be formed, and then destroyed so rapidly that they are never observable. New techniques now make the transients observable and serve to confirm the extraordinary success of the deductive reasoning used to establish their existence.

The story of carbenes is representative. Some 50 years ago, J. U. Nef at the University of Chicago suggested that a large number of reactions might involve formation of divalent carbon compounds as intermediates. However, his observations were based only on inspection of the over-all course of the reactions and later kinetic studies showed that the postulate must be wrong in some cases. Consequently, the mechanistic scheme fell into total disrepute until 1950 when J. Hine published a compelling argument to the effect that dichlorocarbene (Cl_2C:) must be formed in the course of the reactions of chloroform ($HCCl_3$) with strong bases. Although the conclusions were supported by elegant kinetic studies, the observation that originally prompted Hine to resurrect the Nef hypothesis was simple. It had been known for years that chloroform reacts more rapidly with a strong base than do its relatives, methylene chloride (H_2CCl_2) and carbon tetrachloride (CCl_4).

$$\underrightarrow{HCCl_3 > H_2CCl_2 \gg CCl_4}$$

Decreasing rate of reaction with strong bases

From this maximum in the response of reactivity to the structural variation (replacement of hydrogen atoms by chlorine atoms), Hine reasoned that there must exist some mechanism assisted by the addition of a third chlorine atom to carbon but probably entirely inhibited by replacement of the last hydrogen by chlorine. Consequently he formulated

---

*Methylene can be generated in either a singlet in which the unshared valence electrons have opposed spins, or in a triplet in which the electrons have parallel spins. Each species has its own unique chemical behavior.

the following mechanism and confirmed it by means of appropriately designed kinetic tests:

$$\underset{\substack{\text{base}\\\text{(negatively}\\\text{charged)}}}{B^-} + \underset{\text{chloroform}}{H{-}CCl_3} \rightleftharpoons BH + \underset{\text{trichloromethyl anion}}{{}^-{:}CCl_3}$$

$$\underset{\text{trichloromethyl anion}}{{}^-{:}CCl_3} \longrightarrow \underset{\text{dichlorocarbene}}{{:}CCl_2} + Cl^-$$

Hine's suggestion not only settled a puzzling problem in chemical dynamics but also has an important impact on synthetic chemistry. Recognition that dichlorocarbene could be generated from chloroform led to experiments designed to trap the transient by reaction with various kinds of compounds. Many of these experiments were successful and led to development of a host of new synthetic methods and the synthesis of many new compounds.

The first direct unequivocal observation of a carbene was reported by G. Herzberg in 1959. The fact that he was able to observe spectroscopically the decay of one form (the singlet state) of methylene to the other (the triplet state) confirmed completely the earlier conclusions derived from chemical dynamics that there must be two species with different chemical properties.

Modern instrumental methods have recently enabled the direct observation of a large variety of free radicals and carbonium ions. The method of electron spin resonance allows for detection and structural characterization of free radicals in minute concentrations. A recently developed experimental technique, the matrix isolation method, even allows these highly reactive species to be stored for long periods of time. Highly reactive species are trapped in rigid matrices which may be crystals or glasses of some inert material. In the matrix, free radicals are not free to roam so they cannot combine with each other. Stable solutions of carbonium ions have been prepared by George Olah using the exotic solvent, antimony pentachloride. Characterization of these cations, which 20 years ago were often regarded as figments of chemists' imaginations, depends primarily on another new tool, nuclear magnetic resonance spectroscopy. Direct study of reactive molecular fragments is, at the moment, of interest principally to structural chemists. However, the new methods of detection are already being put to work in the study of the dynamic behavior of transients. The possibility for expanding the precision of analysis of reaction networks is most promising.

Many other types of transient intermediates are required to account for dynamic chemical behavior. Included are both electronically excited states of common molecules and molecules that are highly reactive even in their ground states. The former group will be discussed in the section on photochemistry. The latter, far too numerous to catalog, are often compounds closely related to fairly stable, known substances. An interesting example is borane (BH_3), a substance that was once expected to be a stable species. However, it has been known for many years that all procedures designed to generate borane lead instead to the formation of diborane (B_2H_6). Recently, many other boron hydrides have been discovered and it is apparent that there should be a vast system of boron hydrides reminiscent of the multitude of carbon - hydrogen compounds, but having vastly different structural characteristics. The field has been one of the most active areas of synthetic effort during recent years. Attempts to uncover systematic behavior in the reactions of boron hydrides now indicate strongly that borane itself is involved in many of the reactions as a transient. We predict that fairly soon this long-sought species will be trapped in some inert matrix and subjected to direct characterization.

PHOTOCHEMISTRY AND RADIATION CHEMISTRY

Photochemistry is the study of chemical changes brought about by visible or ultraviolet light. The usual exclusion of infrared radiation stems directly from simple principles. When a material absorbs infrared radiation, the molecules are excited to higher vibrational and rotational states and such excitation is ordinarily lost to the total pool of thermal energy of the system before chemical reaction of the initially excited species can occur. The quanta of energy in visible and ultraviolet radiation are larger than in infrared radiation, and, when absorbed, raise electrons in atoms or molecules to correspondingly higher energy levels. Electronically excited molecules often undergo chemical change before they can shed the excitation by other paths.

Radiation chemistry deals with the chemical changes caused by high-energy radiations such as alpha, beta, and gamma rays. When matter is bombarded with such highly energetic species, large amounts of energy are transferred from the rays to the target material. The primary energy-absorption process promotes the acceptor molecules to electronically excited states, suggesting a close relationship between radiation chemistry and photochemistry. There are, however, major differences between the two fields. The amounts of energy in the individual particles of high-energy radiation are much larger than those of quanta of visible or near-ultraviolet light. Consequently, radiation chemistry produces molecules in much higher states of excitation than are involved in photochemistry, and many reactions unknown to photochemistry can be effected by high-energy radiation. Another interesting feature of radiation chemistry results from the fact that the cooling-off of a high-energy particle may produce a number of excited molecules, or transient fragments from them arranged very closely together. Consequently, there is a relatively high probability that the reactive transients will react with each other.

Study of the dynamic processes involved in both photochemistry and radiation chemistry is difficult and fascinating. Many problems arise because the lifetimes of the first excited species are usually extremely short. On the other hand, study of the reaction dynamics is nobly assisted by a large body of knowledge available from spectroscopy—the study of light absorption by molecules and emission of light from their excited states. Spectroscopy, once regarded primarily as a tool of structural chemistry, has now become the most powerful tool available for the study of chemistry induced by all kinds of radiation.

Photochemistry has engrossed scientists ever since the role of sunlight in the growth of green plants was discovered. The understanding of photosynthesis is still far from complete but notable progress has been made during the past two decades. Accomplishment in one area of the field was recognized when Melvin Calvin was awarded the Nobel Prize in 1961. Analysis of the details of the chemical mechanism appears to be progressing well. The use of isotopic-tracer technique has aided in establishing the sequence in which labeled (radioactive) carbon atoms, introduced as carbon dioxide, appear in various metabolic intermediates. Despite an enormous amount of work, the primary process of storing excitation energy after light is absorbed remains largely a mystery. The same is true of the step in which the excitation is converted to chemical energy. However, much progress has been made during the past decade in elucidation of the details of simpler photochemical reactions. Modern photochemistry will provide useful feedback into the problem of photosynthesis but the greatest future for photochemistry may lie in other directions. It is likely that within the next 20 to 30 years chemical methods for harvesting and storing solar energy will make a major impact on the world's economy.

The uniqueness of photochemistry is easily understood. Most chemical reactions require input of energy, either because an activation energy must be supplied to make the reaction proceed at a reasonable rate, or because the desired products have a higher-energy content than the reactants. The most common method for supplying energy is to apply heat. However, this method suffers from the disadvantage that the thermal energy is distributed in a statistical manner among all the components of the system. Individual molecules cannot be raised to high-energy levels without concomitant activation of all other molecules in the system to comparable energy levels. However, bombardment with photons provides a method for selective excitation of individual molecules to highly activated states in an otherwise "cold" system. All of mechanistic photochemistry is concerned with the competition of highly activated molecules to use excitation energy by chemical paths before it is shed by such means as emission of light or conversion of electronic to thermal energy. Molecules excited by absorption of visible or uv light undergo vibrational and rotational as well as electronic excitation. In solution, the molecules usually lose rotational and vibrational excitation too rapidly to allow this part of the excitation to be used for chemical reaction. However, the original electronic excitation may be retained for as long as 10^{-7} or 10^{-8} sec. Furthermore, a large part of the excitation may be trapped for much longer times (seconds to 10^{-5} sec) if the molecule slips into other metastable states.* While times such as milliseconds or microseconds seem short in comparison with the life of a man, they are long in the lifetime of an excited molecule. These times are sufficiently long to allow the excited species to undergo a multitude of exotic chemical changes. Correlation of these changes with the structures of excited molecules is a fast-moving field at the present time.

An especially intriguing aspect of photochemistry involves transfer of excitation energy from one molecule to another. This phenomenon leads to the occurrence of sensitized photoreactions in which light energy is absorbed by one molecule and then transferred to a second which undergoes chemical change.

$$A \xrightarrow{\text{light}} \underset{\text{excited state of A}}{A^*}$$

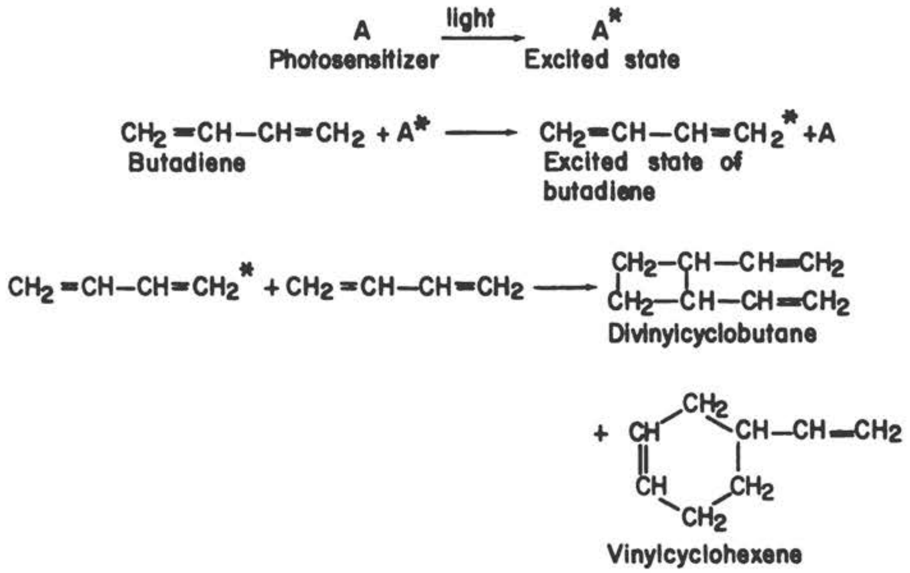
$$A^* + B \longrightarrow A + \underset{\text{excited state of B}}{B^*}$$

$$B^* \longrightarrow \text{products}$$

Such sensitized photoreactions provide a fine clearcut example of the use of structural variation in the study of chemical dynamics. The rate of the chemical change in B is a measure of the efficiency with which excited sensitizer molecules (A*) transfer energy to B. The efficiency of energy transfer has been correlated with the excitation energy available in A*. Because of rapid rate of loss of vibrational and rotational excitation, variation of the wavelength of the exciting light is not an effective means of varying the excitation energy of A* at the time of energy transfer to B. However, the desired study can be carried out by systematic variation of the structure of A. For example, a simple reaction which can be effected by energy transfer is the dimerization of butadiene (the compound is also a principle building block in many synthetic rubbers).

---

*Usually triplet states.



Photosensitized Dimerization of Butatadiene

Use of different sensitizers leads to changes in the relative amounts of divinylcyclobutane and vinylcyclohexene. The variation turns out to be a simple function of the available excitation energy of the sensitizers. Establishment of this relationship led in turn to the recognition that two different excited states of butadiene can be produced by energy transfer; one gives almost exclusively divinylcyclobutane and the other leads to formation of relatively large amounts of vinylcyclohexene. The method of approach—variation in the excitation energy of the sensitizers by varying structure—is called chemical spectroscopy.

The dynamics of chemical change caused by high-energy radiation has been an exceptionally active field of study during the past two decades. Radiation-induced reactions in gases, liquids, and solids have all been studied. The systems given most attention have been aqueous solutions, including biological systems, although a good deal of elegant work has been done recently with other liquid systems. The information derived is of obvious importance in nuclear technology and in understanding the effects of radiation on biological materials. In addition, it provides a new source of information about the chemistry of transient species that are also involved in many thermal and photochemical reactions. Finally, valuable new tools have been developed for initiating useful reactions in the interior of solids by taking advantage of the great penetrating power of high-energy radiation.

Molecules excited by high-energy radiation may fragment into either ions or free radicals. For example, a simple well-known process results in the ejection of electrons. Products are then formed by the subsequent reactions of both the electrons and the residual, positively charged molecular fragments. In many cases the histories of radiation chemical processes are well understood over a time range from 10^{-12} sec after the passage of the radiation up to several minutes later, when all of the reactions are completed.

Consider as an example the chemical effects of cobalt gamma rays on a dilute acid solution of ferrous ions. The observed effect is the evolution of gaseous hydrogen and the oxidation of ferrous ions to ferric ions. The following details describe the presently accepted process. As the gamma rays pass through the medium, they produce, after about 10^{-12} sec, little spherical clusters containing both hydroxyl radicals, OH, and hydrated electrons, e^{-}_{aq}. The latter react with water forming hydrogen atoms and hydroxide ions within about 10^{-13} sec. The H and OH proceed to interact forming H_2, H_2O_2, and H_2O and to diffuse away and react with the solutes (acid and ferrous ions) in the bulk of the solution via a complex mechanism which results in the formation of ferric ions. The reactions between the H and OH are over in about 10^{-7} sec, and with the solutes in about 10^{-6} sec. The hydrogen peroxide (H_2O_2) oxidizes additional ferrous ions within a matter of minutes.

The hydrated electron was detected directly a few years ago by Leon Dorfmann at the Argonne National Laboratory. This was achieved by irradiating the solution with a fast pulse of high-energy electrons from a linear accelerator. The absorption spectrum of the electrons knocked out of water molecules is then monitored on a time scale of millionths of a second. This technique of pulse radiolysis has permitted not only the identification of the solvated electron, but also the measurement of its rate constants for reactions with a host of other free radicals and ions.

Another new field deals with the behavior of atoms generated by nuclear reactions. Perhaps the term radiation chemistry is inappropriate because the radiation-induced changes occur within nuclei, but the chemical aftereffects are nevertheless fascinating. For example, bombardment with neutrons of a system containing helium leads to formation of tritium, the heaviest isotope of hydrogen. These tritium atoms are born with large amounts of recoil energy and their behavior is strongly modified in comparison with ordinary, thermal tritium. The chemistry of these high-energy species is hard to study because they rapidly lose excitation by energy transfer. However, given suitable chemical targets, they react before cooling off. Pioneering study of the special chemistry of hot tritium has been carried out in the gas phase by Wolfgang and his co-workers. They have, for example, studied the reactions of the hot atoms with the following series of compounds: CH_4, FCH_3, F_2CH_2, F_3CH, CF_4. Once again, systematic variation of the structure of a reactant reveals a remarkable amount of detail concerning the reactions. The efficiency of substitution of tritium for fluorine is found to be a sensitive function of the mass of the nonreacting part of the molecule (R).

$$\underset{\substack{\text{Alkyl}\\ \text{fluoride}}}{\mathrm{R{-}F}} + \underset{\substack{\text{Tritium}\\ \text{atom}}}{\mathrm{T}} \longrightarrow \underset{\substack{\text{Tritiated}\\ \text{hydrocarbon}}}{\mathrm{R{-}T}} + \underset{\substack{\text{Fluorine}\\ \text{atom}}}{\mathrm{F}}$$

The result can be reasonably attributed to the effect of the mass of the group R on the rate at which it can turn toward and bind a tritium atom after a fluorine atom has been knocked out of the molecule. Such results promise real insight into the ways in which translational energy can be exploited for chemical purposes in molecular collisions (Section II). Although only a few years ago radiation and hot-atom chemistry seemed to be about as amenable to precise description as the shattering of an egg shell with a sledge hammer, there are now real grounds for optimism that within another decade the principles will be well established.

V

REACTIONS IN BIOLOGICAL SYSTEMS

The last 30 years have witnessed a vast blossoming of knowledge in the chemical dynamics of biological systems. Since living organisms are chemical machines, great effort has been expended to dissect physiological systems into their component chemical reactions. This effort is being rewarded with brilliant success and it is now possible to describe many physiological processes in terms of series of interrelated chemical reactions. Each of these reactions in turn is explicable in terms of simple chemical systems which may be elucidated in the laboratory. This research has led to many advances in our knowledge and control of biological systems and has led to considerable interplay between chemical dynamics and biological dynamics. Consequently, the contributions of chemists, biochemists, and biologists to progress in the field have been so thoroughly intermeshed that it is impossible to delineate progress in the individual disciplines. Contributions have been made by workers in all three fields to each of the problems discussed in this section.

NETWORKS IN BIOLOGICAL SYSTEMS

Reactions in living cells involve the flux of chemicals and energy. These complex reactions have been analyzed in terms of numerous networks of fascinating complexity, usually designated metabolic pathways or cycles. A few examples will be considered here from among the vast number of interesting advances that have great practical importance for both science and society.

The fate of carbohydrates in the cell is an instructive example of an exceedingly complex process brought into a comprehensible pattern. Carbohydrates are a major source of energy for living organisms. The oxidation of carbohydrates by molecular oxygen producing carbon dioxide and water, together with a considerable amount of energy, is a central problem in understanding chemical transformations of the cell. Energy produced in the reaction is used partly for direct production of body heat and muscular action and partly to drive other essential metabolic processes.

Metabolism of Carbohydrates

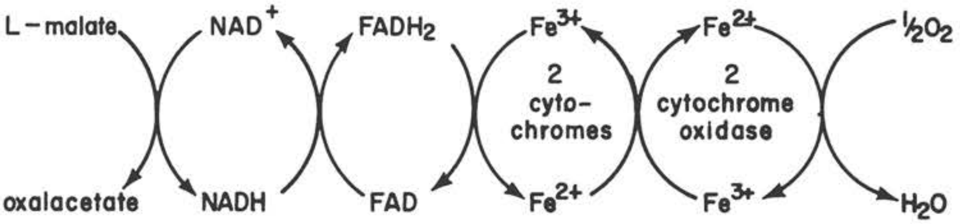
This process, the intermediary metabolism of carbohydrates, may be separated into three parts: (1) an anaerobic (not involving oxygen) phase, called glycolysis, in which sugars are converted through several series of chemical reactions, each catalyzed by a specific biochemical catalyst, an enzyme, into the three-carbon compound, pyruvic acid, CH_3COCO_2H; (2) the tricarboxylic acid cycle, a network of enzyme-catalyzed chemical reactions in which pyruvic acid is converted into carbon dioxide and water, releasing the major quantity of the energy of the original sugar molecules (elucidated principally by Krebs in England); and (3) the electron-transport chain, in which the compounds that oxidize the pyruvic acid in part (2), are reoxidized through a series of enzyme-catalyzed chemical reactions, ultimately utilizing molecular oxygen as the primary oxidant.

Many of the reactions seem deceptively simple when only the overall process is formulated—just as in the case of vapor-phase cracking of ethane (Section II). Results usually show that even simple processes require remarkably intricate chemical machinery to run smoothly in a living organism. An example is the oxidation of L-malate, one of the important compounds in the tricarboxylic acid cycle. The following equation is formulated as though the actual substrate were malic acid, although the reaction probably involves a derivative of that compound:

$$2\,HO_2CCH_2\underset{\underset{OH}{|}}{C}HCO_2H + O_2 \longrightarrow 2\,HO_2CCH_2\underset{\underset{O}{\|}}{C}CO_2H + 2H_2O$$

L-Malic acid Oxygen Oxalacetic acid Water

Coupling of the malate - oxalacetate system to the oxygen - water system actually involves no fewer than four intermediate systems. The complete chemistry can be shown schematically by the following diagram in which the arrows show the flow of electrons (electron transfer = chemical oxidation-reduction) in the coupled oxidation-reduction systems. The entire set of reactions, working like a set of chemical gears, allows rapid oxidation of L-malate by atmospheric oxygen, a process that is slow in the absence of catalytic agents.



NAD and NADH = oxidized and reduced forms of nicotine adenine dinucleotide

FAD and $FADH_2$ = oxidized and reduced forms of flavin adenine dinucleotide

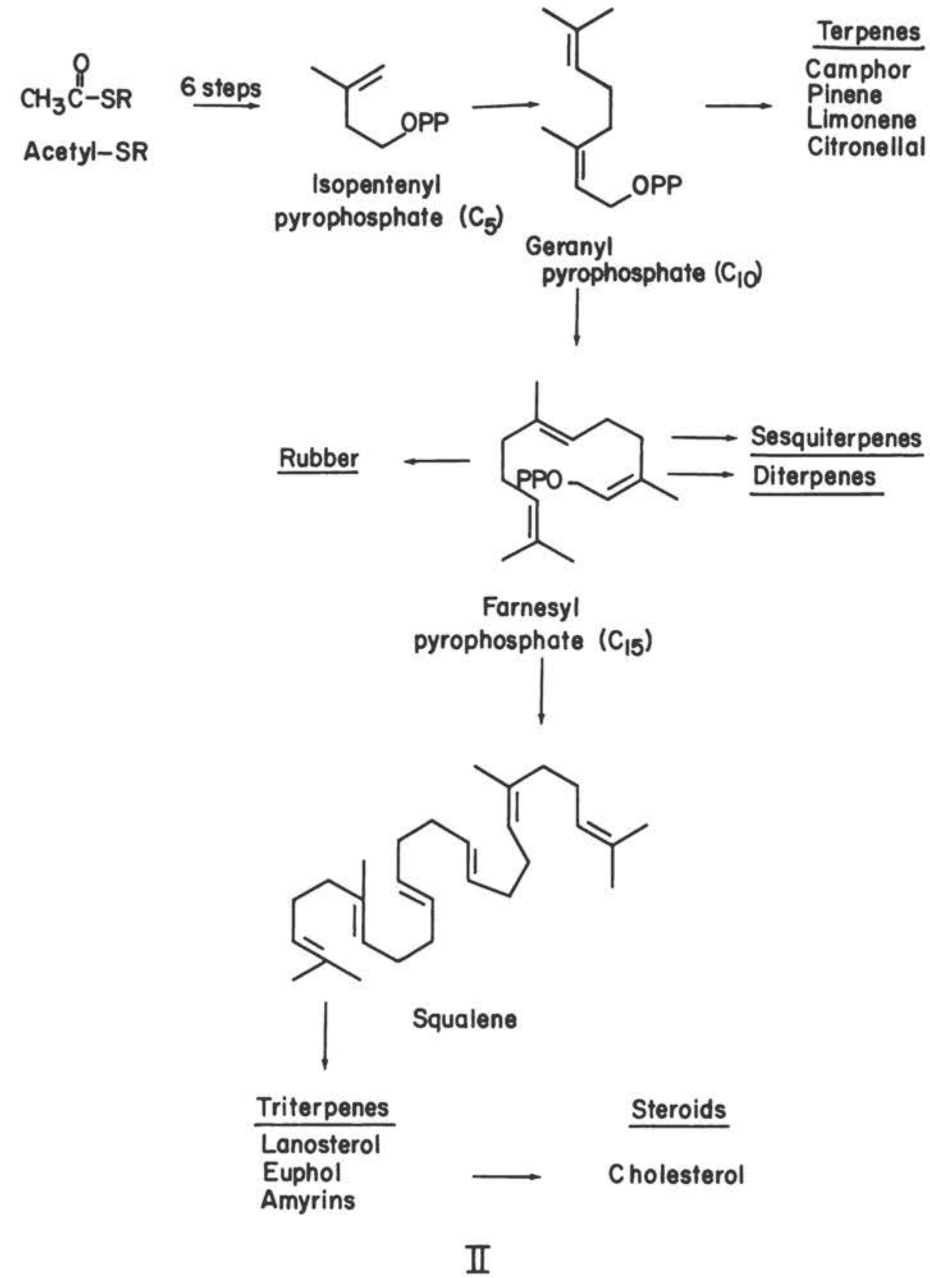
The biological oxidants, NAD and FAD, are complex substances involved in many metabolic processes. The cytochromes are iron compounds in which the metal atom is surrounded by a polyfunctional ligand (Section IV), called a porphyrin. The entire aggregate is bound to a protein. The role of iron in cytochrome-implemented oxidations is related to the function of iron in hemoglobin, the oxygen carrier in blood.

Since the major purpose of the degradation of carbon substrates by a living organism is the production of energy for the development and growth of that organism, the question may be raised about the disposition of this vast amount of energy in the schemes described above. The answer is that most of the chemical energy of the original sugar is transformed into phosphorylated organic compounds which carry out essential chemical processes in the cell. The raw material from which such compounds are synthesized in the body is a salt of phosphoric acid, H_3PO_4. However, the transformation from phosphoric acid to a phosphorylated organic compound is energetically unfavorable until it is coupled with the oxidation process described above. Thus, the process of oxidative phosphorylation is a key phase in the complex network of energy and chemical flux in the cell. Oxidative phosphorylation is intimately tied in with the electron-transport chain shown above, but the mechanism of oxidative phosphorylation is still a field of extremely active research.

This field has achieved so great a degree of sophistication that a detailed computer model of the glycolytic and electron-transport pathway of a particular cell, the Ehrlich ascites tumor cell, has been constructed, consisting of 89 reactions among 65 chemicals including, for example, enzymes, substrates, and complexes. The model is based on the observed steady-state concentrations of all glycolytic intermediates and over-all fluxes from one specific cell preparation, supplemented by data collected from most of the individual reactions. The model quantitatively reproduces much of the carbohydrate metabolism of these cells. It is reasonable to suppose that this is a first step in putting the complex interrelationships together, with the purpose of solving the ultimate problem of the chemical dynamics of the cell.

Biosynthesis of Terpenes

In a completely different area of metabolism, let us consider the chemical dynamics involved in the biosynthesis of terpenes and steroids which has been brilliantly elucidated by Lynen in Germany, Bloch in the United



II

States, and others in recent years. They have shown that a host of complicated organic compounds of plant and animal origin have as their ultimate precursor the two-carbon compound, acetate ion, $CH_3CO_2^-$. Acetate ion in the form of a thiol ester, CH_3COSR, is converted in six enzymatically catalyzed reactions into "biological isoprene," isopentenyl pyrophosphate (C_5), a material, which like isoprene, can undergo polymerization reactions with the formation of new carbon-carbon bonds. Isopentenyl pyrophosphate may be enzymatically dimerized to geranyl pyrophosphate (C_{10}), which eventually leads to a host of terpenes such as camphor, pinene, limonene, geraniol, and citronellal. Furthermore, another C_5 unit may be added enzymatically to geranyl pyrophosphate to produce farnesyl pyrophosphate (C_{15}), which leads to many sesquiterpenes. Farnesyl pyrophosphate has several possible fates: (1) another C_5 unit may be added to it to produce diterpenes such as abietic acid (C_{20}); (2) it may be extensively polymerized to produce the high polymer, rubber; or (3) it may be reductively dimerized to produce squalene (C_{30}). Squalene is the key intermediate in the biosynthesis of all triterpenes, including lanosterol which is transformed into cholesterol and other steroids. Thus a vast area of intricate enzymatically catalyzed reactions and products has been elucidated in terms of a logical controllable framework (see II).

Many other such biosynthetic pathways must be investigated in the future. One of the most important of these is the biosynthesis of proteins, which involves the important problem of the transfer of information from the genetic material, deoxyribonucleic acid (DNA) (Kornberg, Ochoa, and Nirenberg of the United States), to enzymes and other proteins which translate this information into control of the chemical reactions of the cell. Proteins are polymers that are synthesized from approximately 20 different kinds of amino acids in specific sequences, the sequence controlling the structure and thus the chemical function of the protein. A coding of this sequence therefore transfers genetic information from DNA to the protein. Protein synthesis takes place on a cellular particle called the polysome. On this particle resides a polymeric molecule called messenger ribonucleic acid (RNA), carrying in its structure the genetic code which it has already transcribed from the ultimate genetic material, DNA, by a process of complementary matching of individual components of the two molecules. The sequence of chemical components in messenger RNA specifies the amino acid sequence in the protein to be synthesized. Individual amino acids are transported to the proper sites on the messenger RNA by a set of transfer RNA's; there is a specific transfer RNA for each amino acid. A specific transfer RNA chemically recognizes the code for a particular amino acid on the messenger RNA, and thus the specificity necessary for protein synthesis is determined. This description gives only an inkling of the extremely important area of protein synthesis and of the many things that must be done in the future to understand one of the most basic of all chemical processes in the cell.

As a result of basic research on the metabolic pathways involved in protein, nucleic acid, and lipid metabolism, the time has come to investigate some of the more subtle interrelationships of these multienzyme systems. For example, research on the control of metabolism and on the differentiation of cells may eventually contribute to our understanding of cancer. Another area now amenable to study concerns inborn errors in metabolism. It is now possible in the case of the disease, phenylketonuria, to pinpoint the deficiency of a specific enzyme needed for the metabolism of phenylalanine. Thus, if an infant who lacks the enzyme is fed a diet containing abnormally small amounts of phenylalanine, the usual brain damage is prevented.

Eventually it will be found that many diseases result from defects in enzymes or proteins. Another outstanding example is that of sickle-cell anemia (Pauling) in which one amino acid of the normal hemoglobin protein molecule is changed. The biochemical changes at the cellular level associated with learning are also amenable to study now. The time may come when many mental diseases will be specifically ascribed to a deficiency or excess of a specific intermediate or enzyme. With this knowledge, new methods of treatment will become available. The elucidation of metabolic pathways also opens up other new areas of chemotherapy. For example, it is now possible to define, at the enzymatic level, the mechanism of action of various antibiotics, such as oxamycin, actinomycin, puromycin, and chloramphenicol. In fact, essentially every biological system is now susceptible to analysis in terms of chemical dynamics.

INDIVIDUAL CHEMICAL STEPS IN BIOLOGICAL SYSTEMS

When the complex networks of biological systems can be dissected into individual chemical steps, it is then possible to probe into the dynamics of each elementary process. Essentially every individual chemical step is catalyzed by a specific enzyme. Mechanisms of enzymatic catalysis have been investigated intensively and fruitfully in recent years. Besides being the key to ultimate understanding of the chemistry of life, the work carries important implications as fundamental research in catalysis.

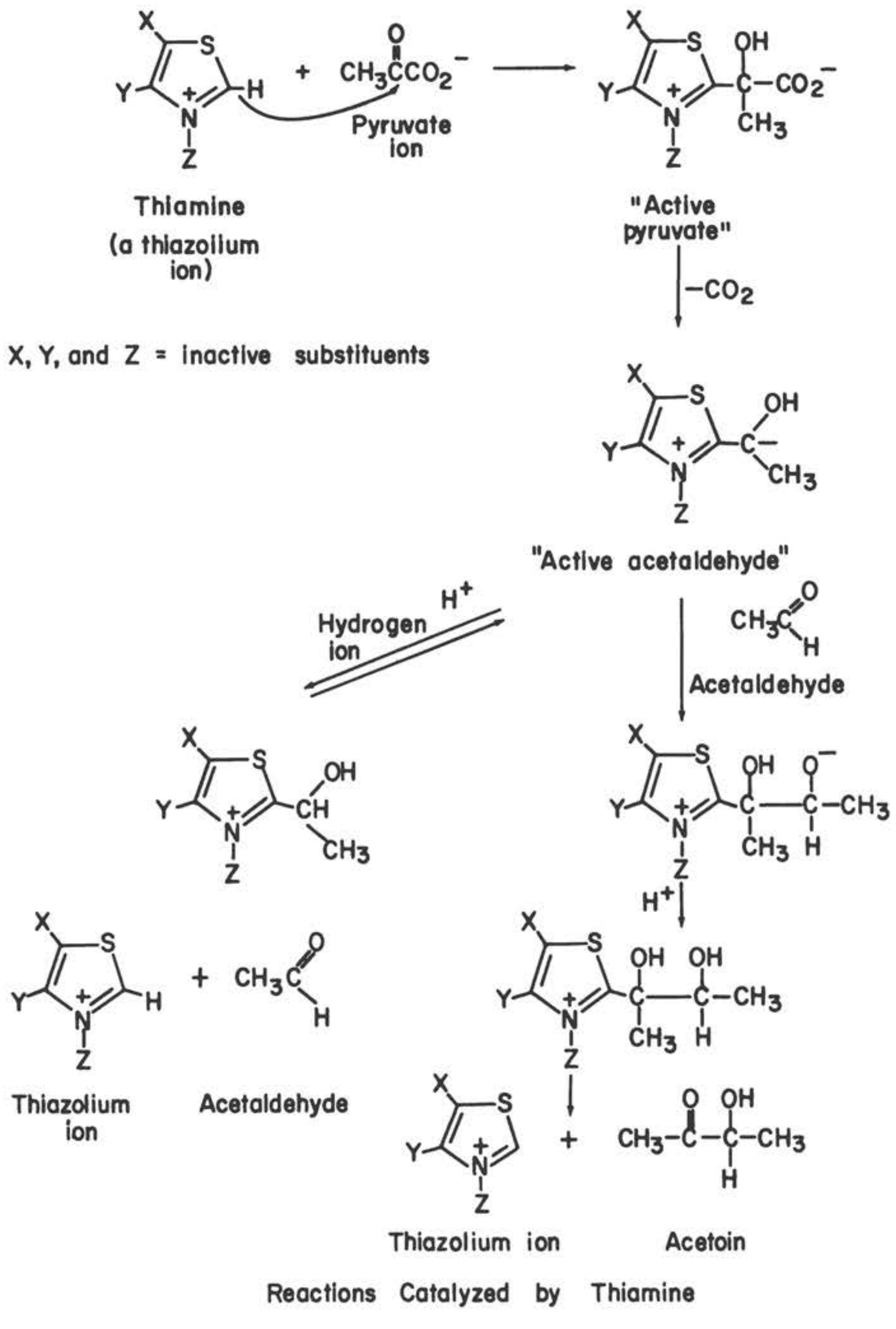
Enzymes are protein molecules of high molecular weight. In some cases the large protein molecule (of molecular weight 25,000) has attached to it a small organic molecule (of molecular weight 200) called a coenzyme. All enzymes contain a discrete number of localized areas, called active sites, which perform the actual catalytic act. These active sites may be associated with the small coenzyme molecules; in such cases the mechanism of action of the enzyme can be duplicated qualitatively (although not quantitatively) by the coenzyme itself without its accompanying, protein backbone. Catalysis by coenzymes has been brilliantly elucidated in several instances, in particular for NAD(niacin)-containing enzymes by Westheimer and co-workers, for thiamine (vitamin B_1)-containing enzymes by Breslow, and for pyridoxal (vitamin B_6)-containing enzymes by Snell, Metzler, and Ikawa.

Thiamine pyrophosphate, vitamin B_1, serves as a coenzyme for a large number of enzymes. Among the simplest of these is the enzyme carboxylase, which catalyzes the decarboxylation of pyruvate to acetaldehyde and carbon dioxide, as well as the formation of acetoin from pyruvate and acetaldehyde. Studies with only a portion of the coenzyme, thiazolium ion, led to unraveling the mechanism of this process in terms of three steps: (1) addition of the thiazolium ion to the carbonyl group of pyruvate, forming active pyruvate; (2) loss of carbon dioxide to give the adduct of acetaldehyde and the thiazolium ion, active acetaldehyde; and (3) dissociation to give acetaldehyde and the thiazolium ion or condensation with a second molecule of acetaldehyde to produce the adduct of acetoin and thiazolium ion. The mechanism shown in the accompanying diagram, elucidated from the model chemical system, was completely confirmed in experiments with the complete enzymatic process. This result is only one demonstration of a host of areas where the understanding of a simple chemical system can be immediately transformed into the understanding of a complex biological system. Catalysis of the condensation of acetaldehyde to acetoin in test-tube experiments is in itself a remarkable phenomenon; the only common chemical known to be a catalyst for the reaction is cyanide. It is not surprising that nature has developed a different catalyst for the process!

The central problem in the mechanism of enzymatic catalysis is the question of how a molecule that is solely a protein can carry out a specific and efficient catalysis. This problem can and has been attacked by investigations on the enzyme α-chymotrypsin, currently under investigation in more than 50 laboratories throughout the world. α-Chymotrypsin, whose physiological function is to hydrolyze protein into amino acids which then can be utilized as building blocks by the body, is a crystalline protein of molecular weight 25,000 which has one active site per molecule.

While the sequence of the 246 amino acids in this enzyme is known at present, the three-dimensional structure of the molecule is not known; it is under active investigation in several laboratories. Despite uncertainty about the geometry of the molecule, it has been possible to probe action mechanism of this enzyme by both model experiments and direct kinetic measurements.

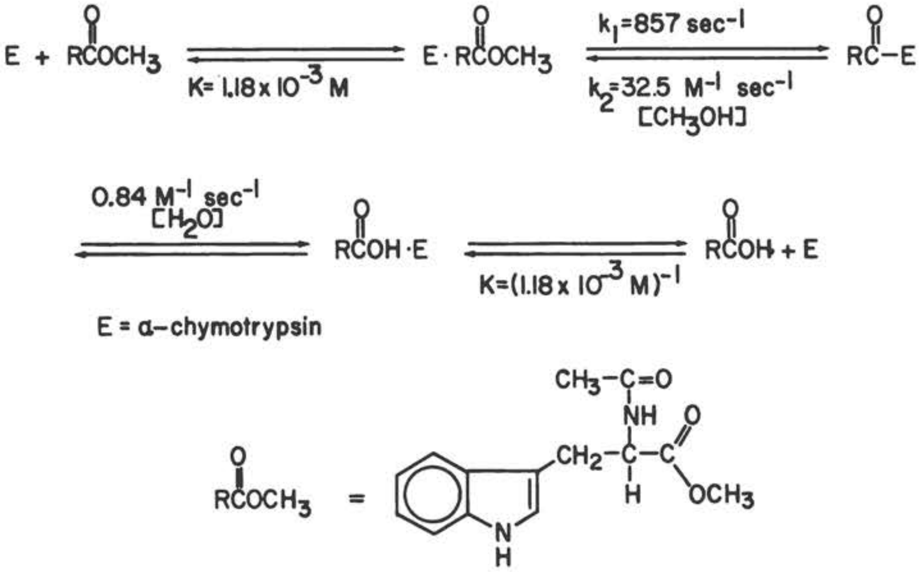
Like all enzymes, α-chymotrypsin forms stereospecific adsorptive complexes with substrates (the substances on which it acts). The specificity of enzymes is related to the complementary fit between the two parts of the enzyme-substrate complex. The topography of the active site of α-chymotrypsin has been investigated by determining the relative fit in the enzyme - substrate complex between the enzyme and a series of synthetic molecules of differing structure, another example of the use of structural variation as a sensitive chemical probe (Section IV).



Reactions Catalyzed by Thiamine

Following the formation of the enzyme - substrate complex, the principal chemical changes take place. A significant breakthrough occurred when it was found that a constituent of the enzyme protein participated in the covalent chemical changes involved in the catalysis. An enzyme - substrate compound, in addition to the enzyme - substrate complex, was detected as an intermediate. This finding has been exploited in developing both insecticides and deadly poisonous chemical-warfare agents. The theory behind the lethal action involves inactivation of vital enzyme systems by chemical destruction of the group that normally takes part in the first bond-switching reaction of substrates.

With discovery of these various intermediates, all the individual steps of the α-chymotrypsin catalysis may be accounted for on a quantitative basis, making it possible to investigate each individual step. The precision with which the elementary reactions can be described is illustrated in III.



III

From a variety of information, including the changes in rates when reactions were run in D_2O rather than ordinary water, the catalytic steps were found to involve rate-determining transfers of hydrogen ions. In neutral solutions the reactions have characteristic time constants of 10^{-3} to 10^{-4} sec. Interestingly, rate constants of this order of magnitude were described by Eigen of Germany as maximal rate constants of simple proton transfer-reactions in neutral solutions.

Knowledge of all the individual steps of the α-chymotrypsin catalysis makes it possible to ask why the enzyme is so efficient and specific. When the α-chymotrypsin catalysis is compared to hydrolysis of the same substrate in an aqueous, alkaline solution, it is observed that the exceptional efficiency of the enzymatic process is associated with an increase in the number of elementary steps. This experimental verification of a long-standing catalytic theory provokes other questions about the reasons for the facile process in each enzymatic step. At present much is still unknown, but it may be stated that the covalent participation of the enzyme, the stereospecific adsorption, the freezing of the substrate on the enzyme surface in a conformation resembling that of the transition state, and the stereospecific placement of catalytic entities of maximal efficiency all contribute to the over-all efficiency and specificity of α-chymotrypsin.

Many other enzymes are well enough characterized to be ripe for the same kind of study that has been devoted to α-chymotrypsin. The magnitude of the whole task is impressive. Hundreds and perhaps thousands of papers have been published about α-chymotrypsin and investigators in the field feel that they have just begun to hit pay dirt.

There are dozens, perhaps hundreds, of enzymes involved in life processes. Chemical dynamicists are usually impatient people, so it is hoped that progress will accelerate. Guidance from the work with α-chymotrypsin will suggest useful shortcuts in the study of the next half-dozen enzymes. Dynamic studies will be complemented by completion of the three-dimensional maps of enzymes by structural chemists using x-ray diffraction methods. Finally, there is always the real hope that sweeping generalizations correlating the behavior of all enzymes (and perhaps all catalysts) will allow us to cut through the whole field with giant steps.

VI
DYNAMICS IN THE SOLID STATE

The chemical behavior of solids has been very important in modern technology for a long time. Solids are the principal components of all structural materials and machinery. The solid state is the most convenient vehicle for production of many exceedingly useful phenomena, including electrical conductivity, heat transfer or insulation, and a host of others. Solids provide protection for people and materials against hostile environments and are universally used for the preservation of man's records and his artistic efforts.

Although a great deal of serious work has been devoted to studying the chemistry of the solid state, the effort has not been commensurate with the importance of the subject until recently. The reason for relative neglect is easily discerned: solid-state chemistry is difficult. The investigator is forever plagued by the difficulty of maintaining constancy in many of the conditions of his experiments. Heat transfer in a solid may be irritatingly slow and transfer of reacting, chemical species is often slower. In no other medium are reactions so difficult to study.

Considerable effort has been devoted to studying thermal decomposition of solids and other exceedingly complex problems, such as the burning of solid propellants. A great deal of important work in such fields as metallurgy and geochemistry is actually in the area of chemical dynamics.

Considerable effort has been directed toward preventing undesirable chemical changes. For example, much work has been directed toward understanding photochemical reactions of films and fibers in order to produce materials that will survive outdoor exposure for long periods of time. Such studies have not yet produced any dramatic development of systematic theory of reactions in solids, but have helped define many important, experimental problems. The problems include difficulties in analyzing the changing system without destroying it, nonuniformity of composition because of slow diffusion-rates in solids, and the fact that heat transfer cannot be implemented by the stirring as is often done with liquid and gaseous systems.

Despite the obvious problems and some timidity about entering a new field where years of work may yield relatively unspectacular results, chemical dynamicists are making some progress in the solid-state field. One of the most interesting studies, carried out by Schmidt and Cohen in Israel, involved the photochemistry of crystalline solids. They found that the course of photochemical reactions is controlled by the orientation in crystals. Similar observations were made in the study of polymerization reactions in solids with monomers oriented by adsorption in the channels inside inert, solid supports known as molecular sieves. In another kind of study it was found that the chemical behavior of hot fragments produced by nuclear reactions is dramatically modified by changing the medium in which the reaction occurs. The nature of the control is easily understood in principle. For example, consider the behavior of a molecule A—B in which the atom, A, undergoes nuclear disintegration to produce a new atom, X. The energy released in the process will be much more than enough to disrupt the molecule and to form free radicals or ions.

$$\mathrm{A{-}B} \xrightarrow[\text{reaction}]{\text{nuclear}} \mathrm{X{-}B}^*$$

$$\mathrm{X{-}B}^* \longrightarrow \mathrm{X}^* + \mathrm{B}^*$$

In the solid state the fragments, X and B, will rapidly lose their excess energy to the matrix and will undergo their ultimate chemical reactions at points near the original site. Furthermore, the locus of secondary reactions caused by local heating will be relatively constrained. Since all reactive species produced as a consequence of the nuclear reaction will be confined to a small volume in the solid, there is a relatively high probability that they will finally interact.

A very active field in solid-state chemistry is the matrix-isolation technique. Highly reactive species can be trapped in inert crystals or glasses and studied directly by means of spectroscopic techniques. Frequently the dynamics of disappearance of these transients can be studied by allowing the solid to warm up to temperatures high enough to allow diffusion in the solid. The technique has advanced to the point where it is routine to perform experiments at temperatures down to 4°K, the boiling point of liquid helium. Consequently, matrix materials such as solid argon can be used as hosts for some of the most reactive molecular fragments known to the chemist.

Important advances have been made in the treatment of migratory electrons and excitations in crystals. These phenomena give rise to electrical conductivity and to many fascinating photoeffects in solids.

Although considerable progress has been made by rather formal treatment of the phenomena using unstructured models, the greatest progress still lies ahead and will involve formulation of the effects as dynamic chemical phenomena. For example, irradiation of crystalline benzene at low temperature with uv light leads to production of long-lived excitations which can be detected by observation of the light that these excitations emit as phosphorescence. Analysis of the spectrum indicates that the excitation is not localized on individual molecules but is shared between pairs. The same delocalization phenomenon is observed in the emission spectrum of crystals of hexadeuterobenzene, the modification of benzene in which all normal hydrogen atoms are replaced by the heavy isotope, deuterium. However, if a crystal is prepared from deuterobenzene containing 1 percent or less of normal benzene as a solute, a remarkable change occurs. The so-called Davydov splitting disappears from the emission spectrum, showing that the excitation has become localized on individual molecules of normal benzene. The excitation must wander through the crystal until it is trapped by normal benzene molecules which have slightly lower energy-levels than the deuterated species. The dynamics of decay, migration, and mutual interaction of the isolated excitations are easily observed and provide a new handle for the study of excited crystals.

Much of the fine work done recently in solid-state physics actually lies in the border area between chemistry and physics. As understanding increases, the physical phenomena will be more and more appropriately discussed in terms of molecular models and more of the work will be carried out by chemists. Although all phases of solid-state chemistry must be developed, we anticipate that dynamic studies will play an outstanding role.

VII

SUSTAINING PROGRESS IN THE FIELD

Vital contributions of chemical dynamics to science have been discussed in this report. It is a common paradox that science can demonstrate exciting growth and at the same time be in danger of severe limitations to that growth. This is the case for chemical dynamics. New, sophisticated, and relatively expensive experimental tools and a large number of bright young chemists entering the field have contributed to the field's rapid expansion and have created a need for immediate increased support to keep the field viable.

A good deal of progress was made for many years with simple apparatus such as burets, constant-temperature baths, and simple vacuum lines. Since many satisfactory experiments can still be carried on with such equipment, the question arises whether new equipment, expensive chemicals, and costly supporting personnel are really necessary. A look at the facts brings forth an unequivocal affirmative answer.

Scientists are not satisfied with poor experiments. Most work 30 years ago would be judged poor by today's standards because the results were nondefinitive or misleading, and the methods were far too slow. It is not feasible for an investigator to work a year on a problem that can be finished in a week by another man in a modern well-equipped laboratory.

The many young chemists entering the field of chemical dynamics can see the obvious attractions of a field that is moving and in which many new things need to be done. At present, however, many young scientists encounter so much economic frustration that they abandon fundamental research after a few years. Others become entrenched prematurely in rigidly fixed programs because the costs of switching to new kinds of problems appear too high. There is a curious enigma in our system which seems to decree that no research group shall have more than one kind of advanced equipment. For example, when a scientist attains stature in the field of molecular beams he is expected to equip his laboratory with the best high-vacuum and detector equipment available. But he may encounter difficulty if he wants to add a few vapor-phase chromatographs, a spectrophotometer, and a scintillation counter for his research group's use in necessary preparative and analytical work.

Costs of research in chemical dynamics come from many sources. Stipends for research workers are significant, but are not a major factor. Since monitoring chemical change is the basis of all experimental work in the field, all kinds of instruments for detection and analysis are its working tools. It is not always clearly understood that much chemical instrumentation is provided on a departmental basis. This is a reasonable procedure, especially when funds are limited. However, many problems in chemical dynamics require virtually continuous use or special adaptation of instruments—requirements often incompatible with community use. Another major problem arises when certain research demands the construction of equipment not available commercially. Such apparatus can be extremely costly and may be useful to only part of one research group. Yet, such exploratory investigations with commercially unavailable and expensive instruments are often at the forefront of the most significant new developments in chemistry.

There are other high direct costs of research. Many useful chemicals are exceedingly expensive; an enzyme chemist may need many thousands of dollars worth of purified enzyme preparations in a year. Substitutes frequently result in false economy. For example, the use of compounds containing unusual isotopes of common elements can greatly simplify a number of problems, but many workers consider isotopic-tracer studies to be a costly last resort. Even when the decision is made to use labeled compounds, the next step is all too often the tedious synthesis of the desired compound from the cheapest available starting material. Thus, the serious researcher in chemical dynamics finds himself wasting time on preparative chemistry to save money. Such work could be done perhaps 10 times faster and more efficiently by an expert in synthesis.

Indirect costs of research can also involve waste of time and talent. Some things to be avoided are research personnel participating in any kind of laboratory or building maintenance; chemists typing their own papers, since their time can be better spent on further research; and chemical stockrooms run on such inadequately small budgets that critical materials are not available when needed.

Many other countries concentrate more of their research in chemistry in national laboratories or in a few government-supported universities than the United States does. For example, nearly all serious research in chemistry in the Soviet Union is carried out in institutes sponsored by its national academy of science. In the United States, fine work is accomplished in both industrial laboratories and in national laboratories such as the National Institutes of Health. Throughout this report it is apparent that a large portion of the significant research in chemical dynamics is carried on in university laboratories and is closely integrated with the education of graduate students. This raises an important question. Are the universities the best location for the nation's principal efforts in fundamental research? Perhaps chemical dynamics could be concentrated in national laboratories or the nation could rely on the chemical industry to do the work.

The latter suggestion can be dismissed quickly. The chemical industry develops practically all commercially important chemistry and contributes in a small but significant way to fundamental research. More is not expected of the industry. There is, however, about a 20- to 30-year gap between fundamental research in chemical dynamics and its industrial exploitation. Few companies could afford much work so far removed from break-even economics. Furthermore, the competitive character of the industry demands that most industrial research be done on a confidential basis. The resulting simultaneous duplication of long-range research in many industrial laboratories would be a waste of the nation's resources.

The question of research in national institutes versus university laboratories is not easily resolved; there are obvious advantages to both. A large institute allows heavy concentrations of research facilities for common use by many persons—a necessity to obtain maximum benefit from such expensive equipment as nuclear reactors or large accelerators. It is true, of course, that many such institutions are located on or near university campuses. A further advantage of the nonacademic research laboratory is that it attracts permanent personnel willing to devote full time to research. University research is usually carried on by students and by postdoctoral fellows working under the direction of faculty members who have instruction as another responsibility. The absence of highly experienced full-time experimentalists may be a weakness of American university research. That this problem is not inherent in the university system is shown by the university laboratories in many West European countries that use semipermanent postdoctoral research personnel.

A principal advantage of university research is the mutual benefits derived from interaction between programs of research and instruction. Undergraduate students benefit so much from contact with research that many liberal arts colleges encourage research by faculty members. Research is the heart of graduate training; conversely, contact with students stimulates the faculty members who direct research. Formal teaching is a bulwark against technical obsolescence. Moreover, a professor is often struck by new insight in his own research program while explaining its principles to his graduate students.

In conclusion, university laboratories, except when large facilities are involved, should continue to be the centers of most fundamental research in chemical dynamics. Only a few projects in chemical dynamics require single items in the $100,000 range. Although the total need for instrumentation and other equipment is large, it is difficult to see how needs can be met by increasing the numbers of chemists in research institutes. Even in medium-sized chemistry departments, instruments shared by the entire department are now usually overworked and frequently unsuitable for specialized applications to research in dynamics. Moreover, a chemist who uses a community spectrometer for monitoring the course of reactions usually keeps the instrument tied up so continuously that it is not accessible to department members who need the machine for other purposes.

Finally, the idea of establishing an Institute of Chemical Dynamics is completely unacceptable. The field is so broad that its people require constant interaction with not only structural and synthetic chemists, but also with physicists and biologists. If such a specialized institute were founded, so many scientists from diverse fields would probably have to be added to the staff that the institution would turn into a colossal institute of general science.